PETROLOGY OF LORD HOWE ISLAND
PART I : THE YOUNGER VOLCANICS

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CONTENTS

Page

I. INTRODUCTION 224

II. PETROLOGY OF THE GOWER-LIDGBIRD LAVAS AND THE YOUNGER DYKES 225

III. MINERALOGY OF THE GOWER-LIDGBIRD LAVAS AND THE YOUNGER DYKES 231

  (*a*) Plagioclase 231

  (*b*) Order–disorder in plagioclase phenocrysts . . . 237

  (*c*) Pyroxenes 242

  (*d*) Olivines 251

  (*e*) Iron ores 253

IV. BULK CHEMICAL ANALYSES 256

V. RELATION BETWEEN COMPOSITION AND DISTANCE FROM RIDGE CREST 265

VI. NOTES ON THE OLDER SERIES 267

VII. BALL'S PYRAMID 268

VIII. AGE OF THE ISLAND 268

IX. SUMMARY AND CONCLUSIONS 271

X. ACKNOWLEDGEMENTS 274

XI. REFERENCES 274

APPENDIX : (1) Petrography of the Gower-Lidgbird lavas . . 277

  (2) Petrography of analysed dyke rocks . . . 284

SYNOPSIS

Lord Howe Island is the only island on the Lord Howe Rise, a major physiographic feature of the south west Pacific, running for 2,000 miles from South Island, New Zealand to New Caledonia. Lord Howe and Norfolk Island, which lies on the crest of a parallel ridge 300 miles to the east, are the only islands in this wide area (2,000 miles from east to west), lying between east Australia and the Tonga Trench, and bounded to the north by New Caledonia and to the south by New Zealand. Lord Howe Island volcanics are of typical alkali basalt composition, but show considerable textural and mineralogical variations. At least three major eruptive periods are represented, the youngest, from radiogenic dating, being of mid-Pliocene age. Vulcanism began at least as early as the Mid-Tertiary and no major change in its character is indicated throughout the period of activity (considered to be at least 20 m.y.). The present island represents only about one percent of its original volume. The upper flows of the youngest volcanic sequence (the Gower-Lidgbird volcanics) show some differentiation towards a trachytic end product. The mean percentages of the significant oxides almost conform to the peak frequencies of these same oxides in islands of typical oceanic character, as recorded by Chayes (1964). There is, however, in each instance a slight but systematic displacement towards the peak frequencies for circum-oceanic basalts. This may be connected with the setting of Lord Howe Island in a sea with a " Mediterranean " type of sea floor structure, and a crustal thickness estimated at 20 km. The degree of silica undersaturation for the Lord Howe Island basalts and for their most differentiated product accords with that of islands displaced a similar distance (just over 200 miles) from the crest of the Mid-Atlantic Ridge. Fifteen analyses of Lord Howe Island rocks are presented ; together with two analyses of their pyroxenes, microprobe analyses of the ores, and optical analyses of plagioclases, pyroxenes and olivines. The order-disorder degrees in the plagioclase phenocrysts, as indicated by the most sensitive optical parameters are discussed.

I. INTRODUCTION

LORD HOWE ISLAND lies 300 miles east of the coast of New South Wales, and about 260 miles west of the crest of the Lord Howe Rise which is a major physiographic feature of the south west Pacific. Lord Howe Island and Norfolk Island, which lies on the crest of a parallel ridge 300 miles further east, are the only islands in this great area of " Mediterranean " type sea-bed crust between eastern Australia and the deep Kermadec-Tonga Trench 2,000 miles to the east. New Zealand borders the southern margin of this sea and New Caledonia and Fiji the northern (Text-fig. 1).

The isolated positions of Lord Howe and Norfolk Islands on submarine ridges having crustal thicknesses of about 20 km. (Officer, 1955) and lying off a continental shelf from which they are separated by only a minor trench (the Ulladulla Trench) divides them, in the oceanographical sense, from the multitude of typical " oceanic " islands on the eastern side of the deep Kermadec-Tonga Trench (with depths to 35,000 ft) and crustal thicknesses of the order of 5–10 km. Lord Howe Island, which lies closer to the mainland and probably has the greater vertical exposures was chosen for prior investigation. It is hoped to compare the petrology of the two islands at a later date. The present paper deals exclusively with the petrology of Lord Howe Island.

Only brief descriptions of the volcanic rocks of Lord Howe Island have been published (David, 1889, and Standard, 1963). There is moreover a difference of opinion between these two investigators as to the relative ages of the two main volcanic formations.

The only account of Norfolk Island petrology is that published by Speight (1913) more than 50 years ago, the main interest of which is the suggestion that enclosures of plutonic origin may occur in the tuffs forming the neighbouring Phillip Island.

The main objectives of the petrological examination of Lord Howe Island were :

1. To determine the number and type of volcanic units of which the island is composed.
2. To investigate the mineralogical, textural and chemical variations in the fresh volcanic rocks.
3. To determine the extent and trend of differentiation in the fresh rocks.
4. To find chemical matches from other provinces for the Lord Howe Island volcanic rocks.
5. To measure the absolute and relative ages of the volcanic formations.
6. To find out whether any petrological changes occurred throughout the period of vulcanicity.

7. To determine whether Lord Howe Island volcanics belong to the " Oceanic " or " Circum-oceanic " petrological types, as distinguished by Chayes (1964).

8. To relate the degree of silica undersaturation of the Lord Howe Island rocks to the distance of the island from the crest of its submarine ridge. (In the Atlantic and East Pacific such a relation has been found to exist).

9. To determine the composition and variation of the four main mineral phases, namely plagioclase, pyroxene, olivine and iron ore ; in particular to investigate the thermal history of the plagioclase phenocrysts.

No arrangements could be made for dredging rocks from the island's submarine slopes and, consequently, the objectives of the expedition could only be partly realised.

In the limited time available for fieldwork (18 days in August 1965) it was impossible to examine systematically all the volcanic units, and consequently the work was mainly concentrated on the fresh Gower-Lidgbird volcanics and the younger dyke swarm. Some of the agglomerate exposures, the more altered groups of lavas and the older, altered dykes were briefly visited. The following groups of volcanic rocks were recognised on the island :

1. A fresh series of horizontal flows, a little over 2,800 ft in thickness forming Mounts Lidgbird and Gower, at the south end of the island. (Gower-Lidgbird series) (Pl. 13, 1 and 2).

2. A dyke swarm cutting the altered lavas in the northern half of the island, but not penetrating the Gower-Lidgbird lavas.

3. A rather altered series of flows, also horizontal, occupying the northern half of the island. The maximum exposure is about 700 ft in Malabar hill, at the NE tip of the island (" Horizontal altered series ").

4. A partly altered series of flows, dipping at 25° to 30° to the SW (i.e. under the horizontal lavas of Mt Lidgbird) and outcropping between Mutton Bird Point and Red Point. About 1000 ft are exposed (" Inclined altered series ").

5. Agglomerates in the lower levels of the inclined altered series; these agglomerates are particularly well exposed at the south end of Blinkenthorpe beach (Pl. 14, 2) and at the south end of Salmon beach.

6. A series of basic sheets and dykes cutting the inclined altered series and particularly abundant in the agglomerates.

II. PETROLOGY OF THE GOWER LIDGBIRD LAVAS AND THE YOUNGER DYKES

About 2840 ft of horizontal flows are perfectly exposed in the cliffs of Mts Gower and Lidgbird (Pl. 13). They are however difficult of access, especially in the upper part where the north ridge of Mt Gower (connecting it to Mt Lidgbird) is the only route. The flows vary greatly in thickness and include several massive horizons 50–60 ft thick with prismatic jointing. A layer of bole forms the upper part of many flows, proclaiming their subaerial weathering. The lowest 250 ft of the Gower-Lidgbird lavas are mainly obscured by scree and can only be collected from the base of Mt Gower, which there was insufficient time to visit. However, the remaining 2500 ft of these lavas was sampled throughout its thickness, a total of forty specimens being obtained. The main features of this group are summarized in appendix 1.

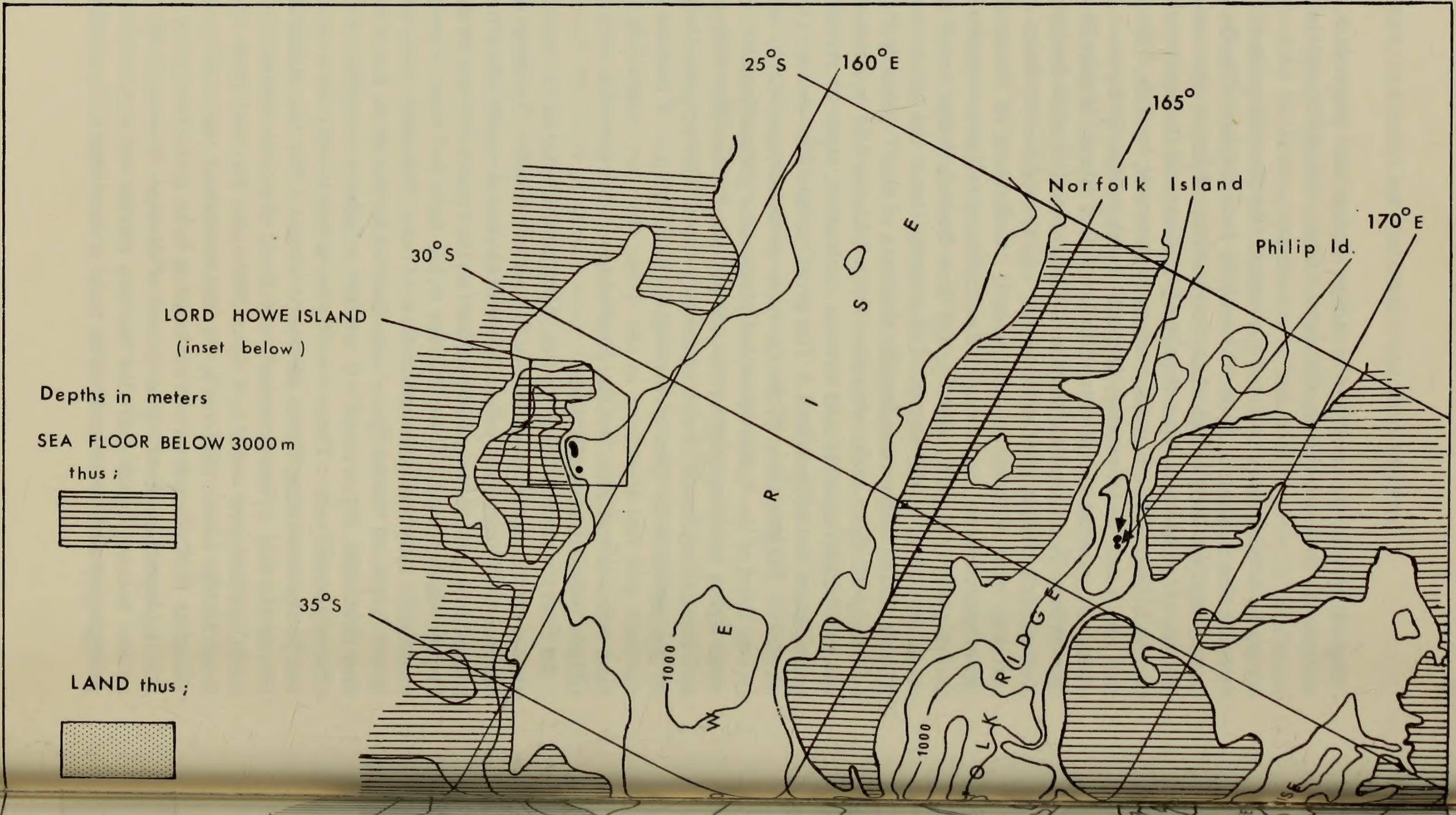
Petrology. With the exception of the cumulate types (from five different heights in the series) and an altered trachytic lava (from an inclined thin sheet near the top of the series) the great majority of these flows belong to the alkali-basalt province, although considerable textural and petrological variations occur. Lavas from most levels are porphyritic with 30% of phenocrysts in some instances (BM.1966, P5, 30). Olivine is the commonest phenocryst. Near the centre of the series (at about the 1500 ft level) there is a group of basalts with very sparse, small phenocrysts. In some lavas (BM.1966, P5, 20, 21, and 22) phenocrysts are virtually absent. Five separate cumulate flows were collected. These are of the oceanite or oceanite-ankaramite type and have up to nearly 60% of olivine plus pyroxene cumulate crystals (BM. 1966, P5, 33 from 720 ft above sea level). Glass is fairly common (18 of the 39 flows) although it only occurs in relative abundance in three flows. Flow structure is well developed in a quarter of the lavas and present in just over half (Pl. 12, 2). The fabric is mainly intergranular, although a well developed sub-ophitic fabric occurs in the intercumulate material of three of the five cumulate types. Olivine (mostly iddingsitized) is present in the groundmasses of most of the lavas and biotite occurs in the groundmass of one lava (BM.1966, P5, 131). A zeolite (chabazite) and carbonate occur particularly in the groups of lavas from near the centre of the sequence. The iron ore consists of ilmenite and/or an ulvöspinel-magnetite.

In the highest flow (BM.1966, P5, 1) a xenolith of hypersthene, calcic plagioclase and a diopsidic augite occurs, the whole being surrounded by a rim of granular olivine. No other xenoliths were noted. In this flow the finely crystallized plagioclase has been partly albitized.

The dyke swarm. The dykes that cut the altered, older volcanic flows are well exposed in the cliffs and wave-cut platforms along the northern half of the island. They are usually vertical or steeply dipping ; the majority strike towards Mt Lidgbird and are roughly radial about this focus. Thickness varies from a few inches to about 15 ft, but the majority do not exceed 6 ft. No composite dykes were observed. The mean spacing of the dykes is about 20 yards, but locally the swarm is very much denser. At three localities (cliffs west of the Old Gulch, cliffs SW of North beach and on Rabbit Island Pl. 15, 1) the dykes are so dense that only remnants of the older lavas can be discerned between them. The more normal spacing is seen in the dykes along the remainder of the North Ridge, where, in the almost vertical cliffs, 80 dykes can be counted spanning a distance of a mile. These are subparallel and perpendicular to the cliff face ; unfortunately sampling is here impossible. Text-fig. 2 shows the positions and trends of all the dykes examined. It is important to note that the dykes do not extend into or intersect the lavas that build Mounts Gower and Lidgbird. (There are perfect exposures on the great cliff faces of these two mountains.) Consequently the relative age of the Gower-Lidgbird series is younger than that of the " horizontal altered series " that forms the northern part of Lord Howe Island, and confirms the opinion expressed by David (1889).

Petrology of dyke swarm. The great majority of dykes have a simple mineralogical composition ; in these olivine is rare or absent and plagioclase, diopsidic pyroxene and ore are the essential constituents. Glass, usually chocolate or khaki coloured is abundant in some dykes and is sometimes associated with analcite. Carbonate occurs as a late stage mineral but before the deuteric period. A feature of many dykes is the infilling of spherical vesicles by minerals of hydrothermal or deuteric origin, mainly soda plagioclase, carbonate, chlorite, ore and (devitrified) glass (Pl. 10, 1). The carbonate, if present, is always at the centre and is the last mineral to crystallize. The plagioclase occurs as acicular crystals. Exceptionally the vesicles are 3 mm. in diameter, but the average size is 1 mm. They are especially abundant in some dykes from Blinkenthorpe beach, Middle beach, and the quarry near Windy Point near the lagoon. They occur less abundantly in the North beach, Ned's beach and Rabbit Island dykes. In the Admiralty Islets and in the few dykes carrying olivine, vesicles are absent. Carbonate of composition $Ca_{31}Fe_{48}Mg_{21}$ (from analysis) and appearing to be of primary origin is common in many dyke rocks and in some (e.g. BM.1966, P5, 83) from Blinkenthorpe beach it forms 15% of the mode and 12% of the norm. Other dykes from the same locality and also from Rabbit Island carry considerable amounts of this " primary " iron-rich carbonate. In nearly all dyke rocks examined both feldspar and pyroxene of the groundmass show, by bent crystals and uneven extinction, signs of strain. The groundmass plagioclases are often zoned. The great majority of dykes (43 out of 52) are porphyritic. Plagioclase is by far the most abundant and widely occurring phenocryst. In one third of the dykes examined plagioclase phenocrysts are abundant, but in the eight dykes carrying porphyritic olivine, plagioclase phenocrysts are absent in five and scarce and small in the remaining three. The porphyritic plagioclase shows a strong tendency to form glomero-groups (Pl. 10, 3). Pyroxene phenocrysts are less common and less abundant in the dykes than are plagioclase phenocrysts. Both tend to be idiomorphic, but the plagioclase always precedes the pyroxene in the intratelluric period of crystallization.

In the rare olivine basalt dykes (8 out of the total of 52 examined), olivine occurs almost entirely as phenocrysts up to 3 mm. in length. In the groundmass it is absent or sparse. The phenocrystal olivines of the dykes usually show incipient alteration to serpentine, and are never iddingsitized as they commonly are in the flows. Although, as previously stated, olivine bearing dykes form but a small percentage of all dykes examined, they are more abundant at some localities than at others. Thus, at North beach, of the 20 dykes examined along the shore line west of the beach only two (BM.1966, P5, 61 and 71) contain relatively conspicuous (but not abundant) olivine phenocrysts. Three other dykes at this locality show rare olivine phenocrysts but in the remaining dykes olivine is absent. On the Admiralty Islets, however, two of the few dykes examined contained plentiful olivine phenocrysts ; 22½% of modal phenocrysts occur in a dyke (BM.1966, P5, 102) from this locality. A dyke from Middle beach (BM.1966, P5, 88) contained just over 30% of modal olivine whilst at Ned's beach an olivine bearing dyke is intersected by, and therefore older than a plagioclase basalt dyke, devoid of olivine. Consequently it is possible that the olivine bearing dykes preceded the non olivine types in order of intrusion. The petrography of five analysed dyke rocks is described in Appendix 2.


25°S
160°E
165°
Norfolk Island
170°E
Philip Id.
30°S
LORD HOWE ISLAND
(inset below)
Depths in meters
SEA FLOOR BELOW 3000 m
thus ;
35°S
LAND thus ;
W E R I S E
O L K R I D G E
1000
1000

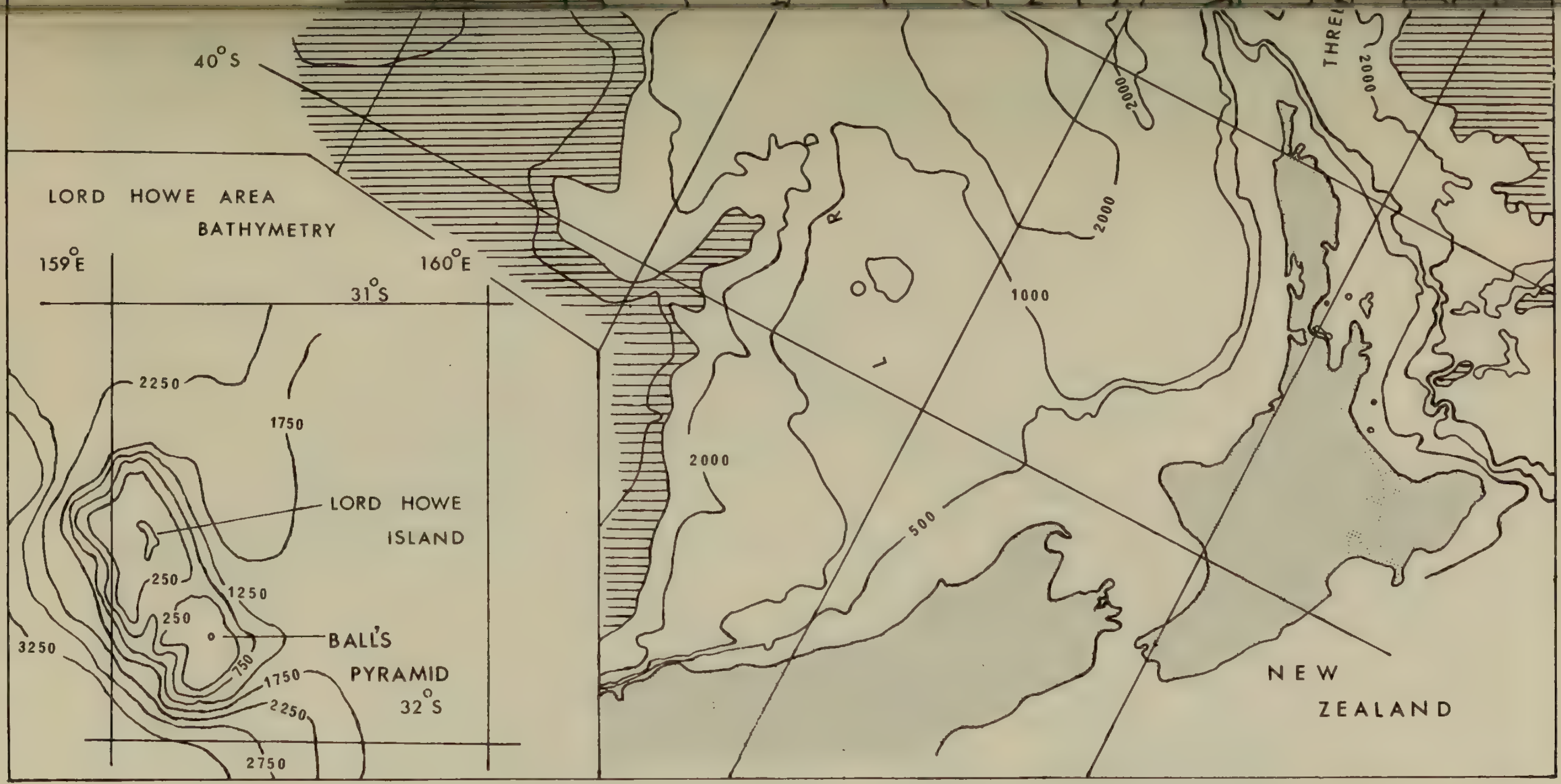


Fig. 1. Bathymetric Chart of Lord Howe Rise and Norfolk Ridge, adapted from van der Linden, 1968.

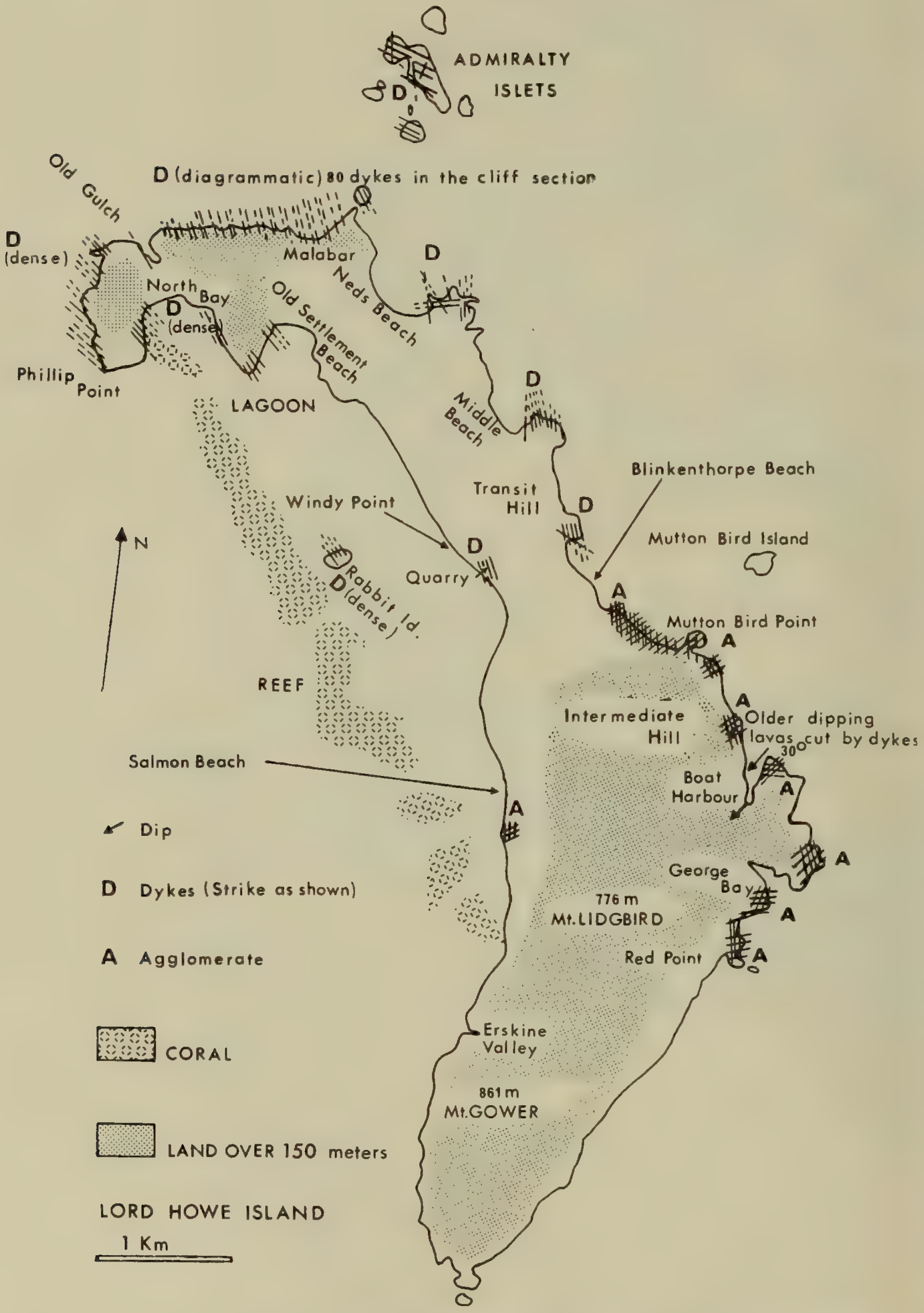


FIG. 2. Map of Lord Howe Island, showing localities and strikes of dykes examined.

III. MINERALOGY OF THE GOWER LIDGBIRD LAVAS AND THE YOUNGER DYKES

(*a*) Plagioclase of the lavas and dykes

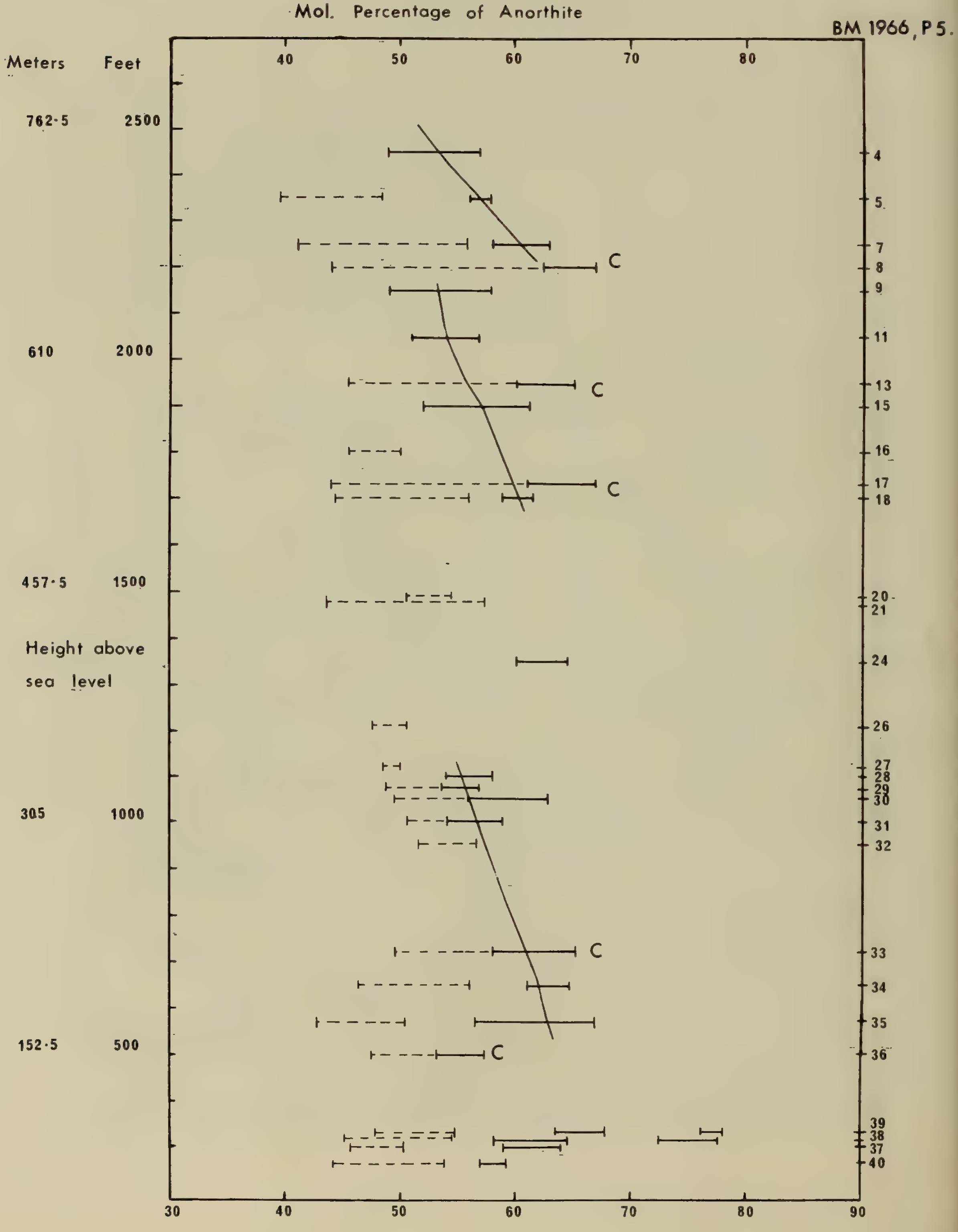
The composition of the plagioclase was determined on a Leitz 4-axis universal stage. For the larger crystals (phenocrysts and the largest groundmass crystals) a full Fedorow technique was used. The twin axis was derived from the positions of $\alpha\alpha_1$, $\beta\beta_1$, and $\gamma\gamma_1$, where α, β and γ are the poles of the indicatrix axes in one member of the twin and α_1, β_1, and γ_1, are the corresponding poles in the second twin member. This technique avoids the use of any morphological plane and gives less scatter in the composition values than do determinations made with reference to a composition or cleavage plane. Having thus derived the twin-axis, the composition of the plagioclase and its twin-law can be obtained from the angles between this axis and α, β and γ, using the curves published by Slemmons (1962) for the various twin laws. The total number of plagioclase phenocrysts thus determined was 138 from the lavas and 49 from the dykes.

The great majority of the groundmass crystals were too small to permit the determination of the indicatrix in each twin member. For these small crystals the composition plane (almost invariably 010) was used as a reference direction and the angle between its pole and the pole of either α or γ was measured. This value was again referred to the appropriate curve on Slemmons' diagram to determine composition (but not the twin law). This method was found to be more precise and less tedious than the "maximum symmetrical extinction angle" method. Optic axial angles were measured wherever possible, but were not used in the determination of composition since the relationship between 2V and composition is not known with precision in volcanic plagioclases (see p. 239). For each flow in the Gower-Lidgbird sequence, and for each selected dyke rock the compositions of five phenocrysts and at least five groundmass crystals were determined. The ranges in compositions are thus directly comparable.

The results of the plagioclase determinations for both lavas and dykes are plotted in Text-fig. 3. This shows no dramatic nor immediately obvious compositional trend. Nevertheless three separate rhythmic cycles can be distinguished for the phenocrystal plagioclase of the Gower-Lidgbird succession ; these are shown in the diagram by inclined lines, trending from relatively more calcic to relatively more sodic plagioclase. In each instance the highest member of the sequence has about 10% more Ab than the lowest member. From near the base to near the top of the Gower-Lidgbird lavas the superimposed effect of these rhythms is to produce a phenocrystal plagioclase (An 55) in the highest levels which has about 10% more Ab than the plagioclase (An 65) near the base.

In the lavas there is usually no compositional gap between the phenocrysts and the groundmass plagioclase. In some lavas it is impossible to draw a definite boundary, i.e. to distinguish two generations in spite of a considerable composition range from the smallest to the largest crystals. Thus a flow (BM.1966, P5, 40) from 300 feet above sea level gave the following plagioclase compositions in passing from the smallest to the largest grains : An 44, 47½, 48½, 51, 54, 54, 57, 57, 57, 57½, 60, 61. The accumulate lava types show similar effects. An oceanite from 2200 ft above sea

A. GOWER LIDGBIRD LAVAS



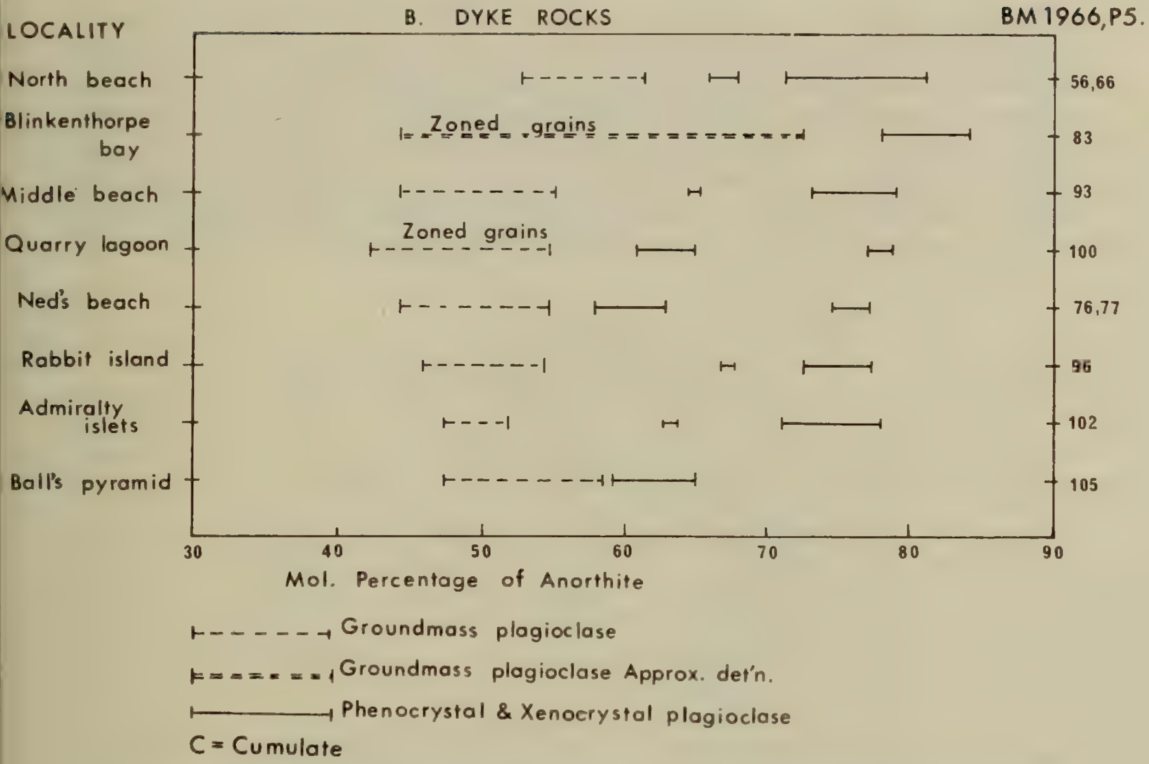


FIG. 3. Compositions of plagioclases from (A) the Gower-Lidgbird sequence and (B) selected dyke rocks from eight different localities.

level (BM.1966, P5, 8) showed progressive increase, by roughly equal instalments, from the smallest grains (An 44) to the largest (An 67).

In the lavas xenocrysts (An 73 to 78) occur only in the lowest flows, and even here they are uncommon. By contrast, the larger plagioclase crystals of the dykes contain a plentiful array of bytownite xenocrysts (An 71–84) in addition to the rarer phenocrysts (An 58–68).

The plagioclase from the dykes, in contrast to that from the lavas, shows a compositional gap between phenocrysts and groundmass which sometimes exceeds 10% An. A dyke (BM.1966, P5, 96) from Rabbit Island for example has groundmass plagioclase of composition An 46–54, while its phenocrystal plagioclase has a composition of An 67.

Some dykes contain several types of larger plagioclase crystals. An example of the complexity that may occur is given by the plagioclases from a dyke 6 ft wide (BM. 1966, P5, 56) outcropping just west of North beach. The plagioclases from a single section of this dyke included:

(1) Normal phenocrysts in the form of clear, idiomorphic, prismatic crystals having a mean composition of An 66.

(2) Subidiomorphic and somewhat corroded grains, often in glomero-groups, containing abundant inclusions of pyroxene, ore and glass, giving them a " spongy " or "checkerboard" appearance (Pl. 10, 4). These plagioclases also show some degree of preferred orientation. Many are normally zoned having bytownite cores (An 70–77), proceeding outwards with some discontinuities, to exteriors of andesine (An 44–48). A few grains of apparently uniform composition have very narrow sodic rims. Pericline and Ala twins are confined to these spongy plagioclases, being absent from the remainder which have albite or Carlsbad twins.

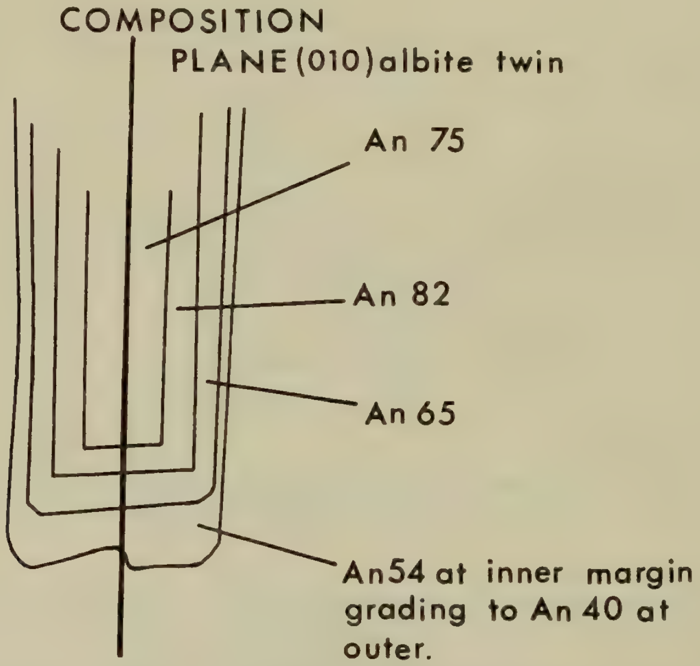


FIG. 4. Diagrammatic sketch of crystal from dyke at North beach, showing oscillatory zoning.

(3) Clear idiomorphic, lath-shaped or prismatic crystals (presumably xenoliths) of bytownite (An 73–81) often occurring in glomero-groups. They are either unzoned or have narrow exterior rims or terminations with an average composition of An 65. These crystals show, dominantly, Carlsbad twinning.

(4) Crystals with oscillatory zoning ; these occur singly. Several idiomorphic examples occur, of which one is illustrated in Text-fig. 4. The composition of each shell is shown in the diagram. The extreme range in composition in this crystal is from An 40 to An 82. In Pl. 11, 1 a discontinuously zoned plagioclase (two zones only) is shown. The example just quoted illustrates the variety and complexity of the so called phenocrysts from the dyke rocks.

Twin laws. The distribution of twin laws in the phenocrysts of the lavas and the dykes is given in Table I. In both the lavas and in the dykes, albite, Carlsbad or albite-Carlsbad twins comprise nine-tenths or more of all twins that occur. The percentage of twins recorded as albite-Carlsbad tends to be higher than it probably should be because very thin lamellae often separate the two main twin members. Many twins recorded as albite-Carlsbad are probably albite plus Carlsbad twins. These two types (albite and Carlsbad) account for over three quarters of all twins, and there is no essential difference in twin laws shown by plagioclases from the lavas on the one hand and from the dykes on the other.

TABLE I

DISTRIBUTION OF TWIN LAWS IN PLAGIOCLASES IN LAVAS AND DYKES

Twin law	% in lavas (69)	% in dykes (52)
albite	39	28
Carlsbad	30½	43
albite-Carlsbad	20	23
pericline	6	4
ala	1½	2
Manebach	3	—

Groundmass plagioclase. Text-fig. 3 shows that above 2200 ft the groundmass plagioclases of the Gower-Lidgbird lavas follow the trend of the phenocrysts towards enrichment in albite, but below this level there are no definite changes. Similarly the plagioclases from the groundmass of the dykes show no definite trend. Its mean composition from the eight different localities all lie within 5% An of the overall mean (An 52) and thus show no significant variation with locality. Text-fig. 5 shows the distribution of composition of the unzoned, or very slightly zoned, groundmass plagioclases of the lavas and dykes. There is a close correspondence between both the mean compositions and the degree of scatter. The two means differ by less than 2% in An content, and this difference is partly due to the inclusion of groundmass plagioclase from the upper flows, which as already mentioned, is somewhat more sodic than the bulk of the groundmass plagioclase from the main part of this sequence.

Zoning is common in the groundmass plagioclase of the dykes and also in the smaller plagioclase grains of the accumulate type of lava, in which crystals with a core of composition approximating to An 50 have exteriors of An 30–35. In those lavas in which the two generations of plagioclase are sharply contrasted, zoning of the groundmass plagioclase is both less common and less intense ; differences in composition between cores and exteriors are of the order of An 10 to 15. The twin laws of the groundmass plagioclases are usually impossible to determine, but the composition plane was found to be 010 in 97% of all measured grains and 001 in the remaining 3%.

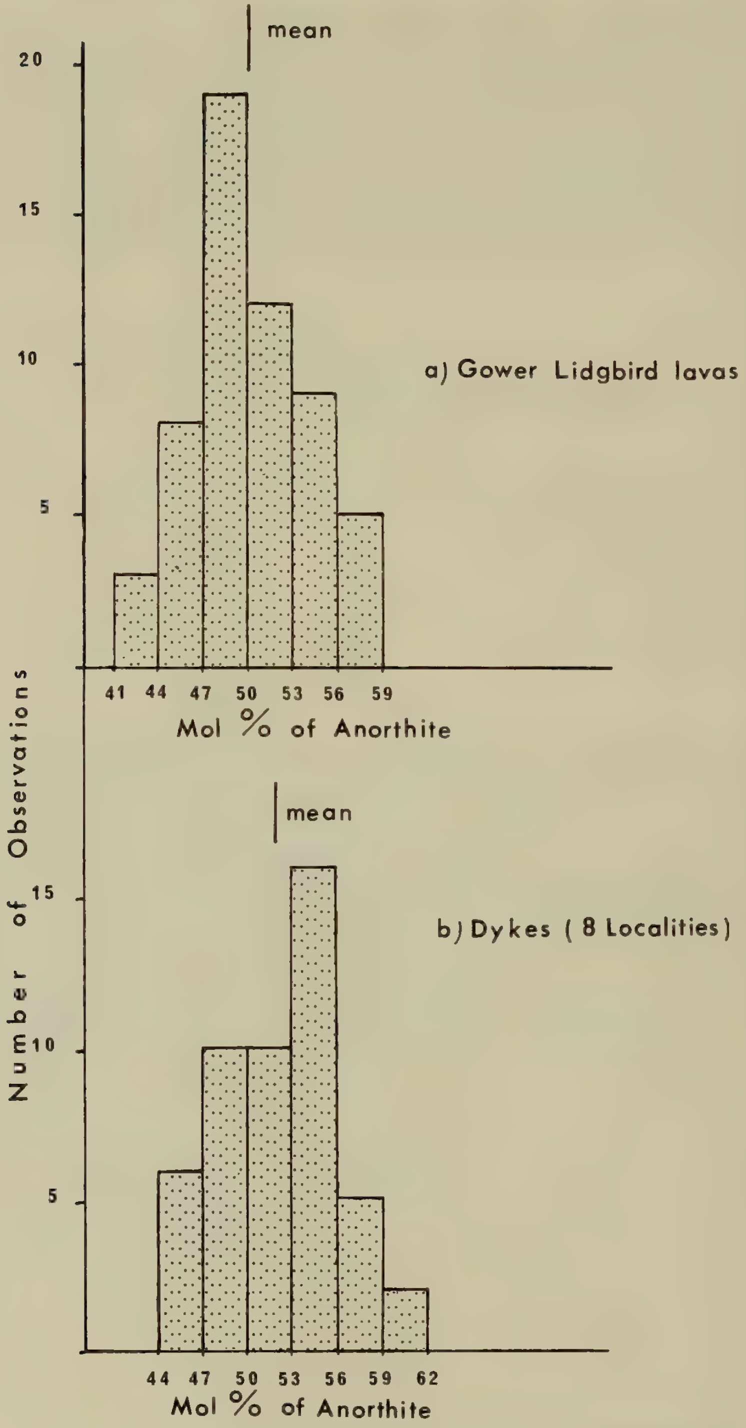


FIG. 5. Distribution of composition of plagioclase in groundmass.

(*b*) Order-disorder in plagioclase phenocrysts

In measuring the composition of the plagioclase phenocrysts in the Gower-Lidgbird series and the dyke rocks by the most accurate optical techniques possible (i.e. without recourse to any morphological planes the data accumulated are considered sufficient to warrant drawing orientation curves for two twin laws and a mean optic axial angle curve ; these curves are for volcanic plagioclases in the An 50 to An 85 composition range. The object was to investigate the degree of ordering of the lattice and also, in the case of 2V, to try to produce a reliable curve (or " band ") in this region where, as Marfunin (1966) so truly states, " data are contradictory and inadequate ".

Text-fig. 6 shows the value of $\alpha\wedge$ twin axis and $\beta\wedge$ twin axis for plagioclases having albite-Carlsbad twins (T.A. = $\perp[001]$ in (010)) and for plagioclases having albite twins (T.A. = $\perp(010)$). The curves published by Slemmons (1962) are also shown. Although Slemmons' curves for the limiting states of albite-Carlsbad twinned plagioclases (completely disordered high-temperature and completely ordered low-temperature plagioclases) are separated by less than 2° in the region An 50 to An 70, the plot for the Lord Howe labradorites shows that this is a real difference that can be measured. All points for these feldspars are above Slemmons' low temperature curve. They show an almost even distribution on each side of his high temperature curve. There is however, in the An 60 to An 70 region a very slight, but probably significant tendency to a state not completely disordered in a few grains. Thus, in the total of 45 points, all except three are less than 1° from the high temperature curve. The three exceptions—all exactly 1° from the curve—lie on the low temperature side of it. However the evidence is far too slender to try to derive any quantitative value for the " degree of ordering ". For plagioclases having albite twins and more calcic than about An 70 the optical differences are less than 1°, and it is impossible to derive any information about order-disorder. But, from An 70 to An 50, the optical differences become progressively more marked At An 50 the difference between the angles for the extreme states is 6½° and therefore easily detectable. For crystals with albite twins, the standard deviation of $\beta\wedge\perp 010$ (the angle that expresses the degree of order-disorder) as determined from 20 sets of 5 repeated measurements on the same crystal is 0°·38. Consequently differences exceeding 1° (nearly three times the standard deviation) in this angle cannot be ascribed to experimental error, but are probably the result of different degrees of ordering in different crystals. The actual crystals measured, with compositions from about An 46 to An 54, are symmetrically disposed about the high temperature curve. It must be concluded (admittedly on the basis of only four determinations) that these plagioclases which are the most sodic phenocrysts in the Lord Howe volcanics are disordered high temperature types. From An 55 to An 67 there are 18 determinations ; of these 4 lie below the high temperature curve and 12 above (on the low temperature side): 6 of these 12 are displaced from the high temperature curve by 1° or more. In this limited compositional range, therefore, there is sufficient evidence upon which to base an " intermediate " curve (I–I in the figure).

If, following Uruno (1962) and Slemmons (1962) we try to evaluate order-disorder

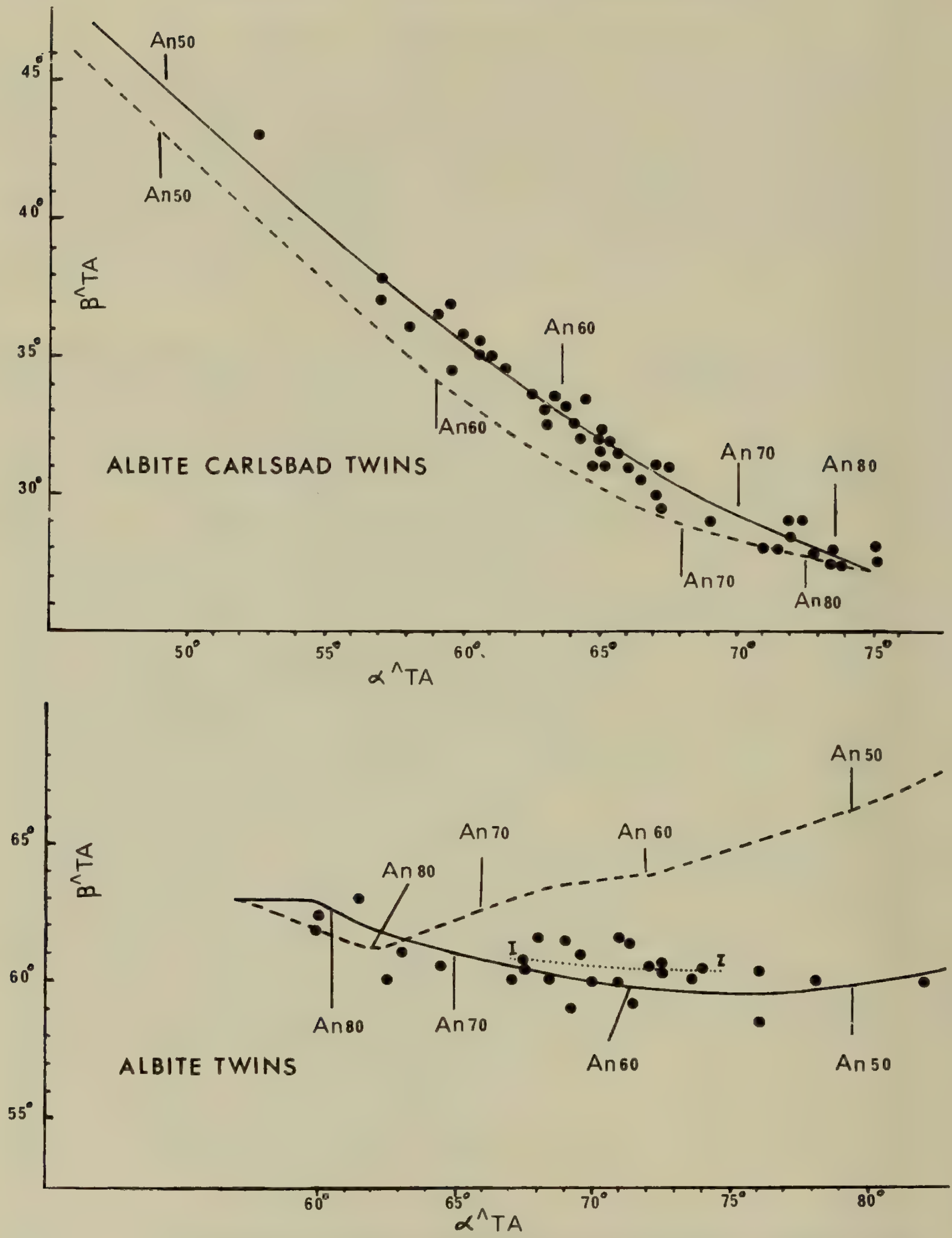


FIG. 6. Relation between α^ twin axis, β^ twin axis and composition for plagioclases from the Gower-Lidgbird lavas and from the dyke rocks. The solid lines are Slemmons' curves for high temperature plagioclases. The broken lines are Slemmons' curves for low temperature plagioclases. The dotted line I–I is the "intermediary index of ordering" curve.

by using an index of 0 for the most disordered form and an index of 1·0 for the most ordered form, and assign intermediate indices to intermediate types according to their positions relative to the 0 and 1·0 forms, we obtain for the I–I curve, in Text-fig. 6 an intermediate index of about 0·2, since this curve lies about one-fifth of the total distance between the high temperature (disordered) and low temperature (ordered) curves. This figure (0·2) agrees with that given by Uruno in his abstract (plagioclases in fresh volcanic rocks—0·2) although he quotes a figure of 0·28 in a later table (Table 8). It also agrees exactly with the value obtained by Slemmons for his " intermediary " index obtained from X-ray measurements $[2\theta(131)-2\theta(1\bar{3}1)]$ for plagioclases in the An 60 to An 70 compositional range. However, since there are, in all, three points lying 1° or more below the high temperature curve drawn by Slemmons there may be some evidence that this curve does not represent a state of complete disorder but should be displaced slightly downwards.

Text-fig. 6 therefore suggests that, although many plagioclases from the Lord Howe fresh volcanic rocks are completely disordered high temperature types, there are a minority that show some degree of ordering. This finding is in agreement with that of Uruno (1962) who notes that whilst the majority of plagioclase phenocrysts in volcanic and hypabyssal rocks show low ordering, there are some that are more ordered.

Optic axial angles. Text-fig. 7 shows the values of 2V for those plagioclases (a) in which both optic axes were within the field of view and (b) the composition of which was regarded as having been accurately determined (triangles of error for the twin axis small or non-existent). The figure includes values of 2V published by van der Kaaden (1951) and a few by Köhler (1942) for volcanic plagioclases. Of the total of 104 values, one half lie within a belt extending 1½° on each side of the " best fitting " curve. An angular error of 1½° corresponds to a compositional error of about 5% in the An 50 and An 75 regions where the curve is " flat " but to an error of only about 1½% An in the An 60–An 70 region where the curve is relatively steep. Thus the 50% chance of estimating the composition from 2V for volcanic plagioclases with compositions between An 50 and An 85 varies from 1½ to 5% An. 15 per cent. of points lie 3½° or more from the curve. There is, therefore, a 15% chance of making an error of from 6% to 7% An in determinations derived from 2V measurements. Consequently 2V is of only secondary value as a guide to composition.

The 2V values obtained by van der Kaaden, by Köhler and by the author for volcanic plagioclases in this range (50 to 85 An) are in mutual agreement, permitting the drawing of the curve shown in the figure. But this mean curve is completely at variance with two curves derived by Smith (1958) for low temperature and high temperature plagioclases within these compositional limits. The discrepancy can be seen by reference to Marfunin's (1966, fig. 56) diagram in which van der Kaaden's curve is contrasted with the curves published by Smith. As Marfunin remarks " low temperature curves of Smith almost coincide with high-temperature curves of van der Kaaden ". Smith's high temperature curve was based on only three points in the An 60 to An 80 range, and these were obtained by heating plagioclases considered (from X-ray evidence) to be " the lowest temperature plagioclases so far found ". The paucity of points on the high temperature curve might explain the

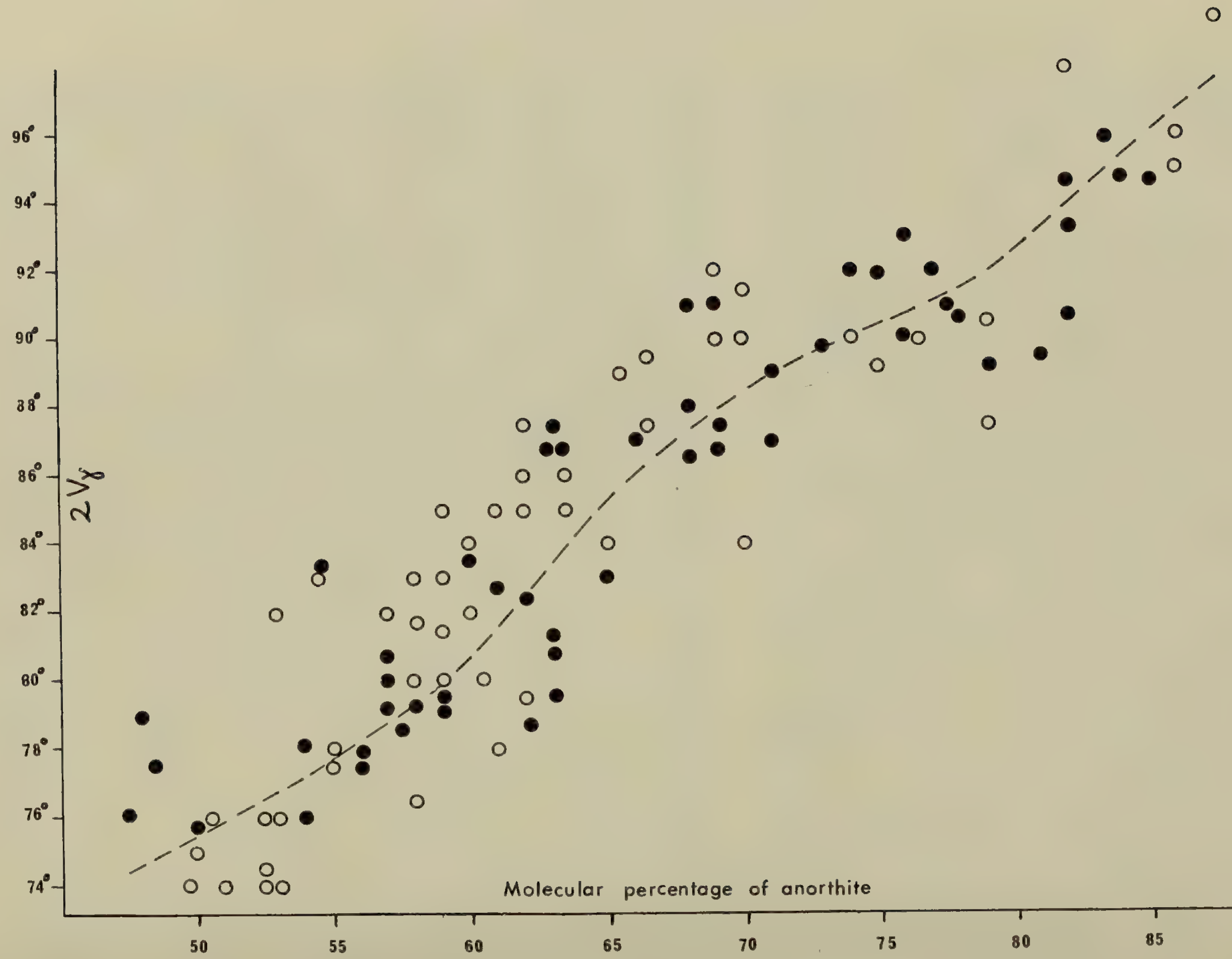


FIG. 7. Values of $2V_\gamma$ for volcanic plagioclases. The solid circles represent the values for Lord Howe Island plagioclases. The open circles represent the values given by van der Kaaden (1951) and by Köhler (1942) for other volcanic plagioclases.

discrepancies noted here, but Smith's low temperature curve is based on eight values (An 55 to An 85) and it seems impossible to explain the difference between this curve and those obtained by other investigators. Uruno (1962) has published values of 2V for plagioclases with an " ordering degree " of 0·6 to 0·8 (presumably not volcanic plagioclases) and the curve obtained from his values does not differ greatly from Smith's low temperature curve

The average width of the " zone of scatter " for 2V for volcanic plagioclases of compositions from 50 An to 85 An, as measured by Köher (1942), van der Kaaden (1951) and the author is from 6° to 8°. This is about the same as the angular variations published by Smith between his " completely low temperature " and " completely high temperature " curves. All the facts indicate that Smith's limiting curves should lie further apart, and that their trend cannot be accepted for volcanic plagioclase. The standard deviation for 2V determinations, as derived from 20 sets of 5 repeated measurements (resetting the optic axial plane for each set) is 0·33°. Consequently the maximum experimental error (three times the standard deviation) is 1°. Similar considerations show that the maximum error in the determination of composition is 2% An in the An 50–65 range and 3% An in the An 65–85 range. The probable errors are less than one-third of these amounts. Therefore, a scatter of 6° to 8° in 2V is far outside the limits of experimental error. The " phenocrysts " of basalts must have had widely differing thermal histories, producing different degrees of order-disorder. This is consistent with the fact that in BM.1966, P5, 56 (see p. 233) at least four differing types of plagioclase were found in a single dyke. Variations in order-disorder degree are not confined to the phenocrysts. Two pairs of xenocrysts (one pair from the same section) the members of each pair having virtually identical compositions (An 77 for one pair and An 81 for the other) have 2V values differing by 2·5°. It is, of course, possible that a varying proportion of other elements could partly account for the differences noted in 2V for plagioclases of the same essential composition. The elements most suspect are Ba, Sr, and Fe. A microprobe analysis was made to determine the amounts of these elements in two plagioclases from adjacent flows (BM.1966, P5, 37 and 38) at the base of the Gower-Lidgbird series, having identical compositions (An 62) but optic axial angles differing by 5½°. The results were :

TABLE II

VALUES OF 2V AND THE PERCENTAGE OF Ba, Sr, Fe AND Ca FOR PLAGIOCLASES FROM TWO ADJACENT GOWER-LIDGBIRD LAVAS

BM.1966, P5	2V	Ba	Sr	Fe^{+2} Fe^{+3}	Ca
37	81·2°	0·39	0·12	0·71	10·12
38	86·7°	0·09	0·18	0·52	9·75

It is impossible at present to evaluate the effect of these differences in the distribution of these minor elements, but it is worth noting that differences, especially in the Ba content, exist. Determinations on synthetic plagioclases incorporating known amounts of these elements might indicate their influence. Meanwhile there is a need for many more measurements of volcanic plagioclase optic axial angles, after precise determinations of their composition. Slemmons' (1962) diagrams indicate that this parameter shows greater variations than do the X-ray reflection differences, based on measurements by Smith (1958) and by Smith and Yoder (1956) for two pairs of strong peaks that are sensitive to structural changes, namely $2\theta(131)$–$2\theta(1\bar{3}1)$ and $2\theta(1\bar{3}1)$–$2\theta(220)$. The only conclusion that can at present be drawn for basaltic plagioclase phenocrysts is that they show marked differences in their order-disorder relationships which indicates that their rates of cooling must have varied within wide limits, suggesting different depths of derivation. Smith (appendix to Hess, 1960) suggests that useful information might be gained about the structural complexities of plagioclases by separate determinations of the " optical properties of extensive groups of samples of comparable thermal history ". But the trouble is that, in basaltic rocks, it is impossible to recognize crystals of " comparable thermal history ". Such rocks contain (even in a single section) groups of crystals which have had different rates of cooling.

(*c*) Pyroxenes of the lavas and dykes

Pyroxene is present in the groundmass of all the flows of the Gower-Lidgbird sequence and in the dyke rocks. The modal proportion of pyroxene is usually 30 to 35%. Much of the groundmass pyroxene, especially in the dykes, shows evidence of strain. Pyroxene occurs as phenocrysts in about 50% of the flows and 70% of the dykes, but it is only abundant in about a quarter of the flows and 10% of the dykes. In the dykes the pyroxene phenocrysts are usually sparse and small and much less plentiful than the plagioclase phenocrysts, around which they are often moulded, being of later crystallization. In both dykes and flows pyroxene tends to form glomero-porphyritic groups (Pl. 12, 4). In some of the lavas larger, single pyroxenes occur, up to 1 cm. in diameter. Most pyroxene phenocrysts from both flows and dykes tend to be idiomorphic (Pl. 12, 3); twinning on 100 is common.

Although the relations between composition and optical properties are insufficiently well known to derive absolute compositions, measurement of 2V and the refractive index provides a useful means of detecting any compositional variations throughout the sequence. These parameters were therefore determined for phenocrysts, and, wherever possible, for groundmass pyroxenes of both flows and dykes.

The refractive index (γ) was determined by the single variation method, using sodium light and iodonapthalene. The grains were placed in this liquid on a hot stage which was connected, in parallel, to an Abbé refractometer. Hot water was circulated through this system, and the temperature was varied until an exact match was obtained. The refractive index was then obtained, directly, from the refractometer reading. For the 2V measurements a Leitz 4-axis universal stage was used, and only those determinations were accepted in which direct observation of both axes was possible. γ^C was also determined where possible, on twinned crystals using the method of Turner (1942).

The results of the optical determinations are given in Table III. It is evident from this table that whilst the composition of the two pyroxene generations differ there

TABLE III

REFRACTIVE INDICES (γ), OPTIC AXIAL ANGLES AND $\gamma \wedge C$ VALUES FOR CLINOPYROXENES OF THE GOWER-LIDGBIRD LAVAS AND OF THE YOUNGER DYKE ROCKS

Lavas

BM.1966, P5	Height a.s.l.	RI(γ)		$2V_\gamma$ (mean value)		$\gamma \wedge C$
		Phenocrysts	G-mass	Phenocrysts	G-mass	
4	2400 ft	1·718	—	53·6°	—	—
7	2300 ft	—	1·737	—	49·2°	—
8	2200 ft	1·726	—	53·7°	—	—
13	1950 ft	1·725	—	53·0°	—	—
17	1750 ft	1·724	—	53·2°	—	—
18	1700 ft	1·720	—	53·6°	—	45°
24	1300 ft	—	1·733	52.7°	—	—
31	950 ft	1·722	—	—	—	—
32	900 ft	1·722	—	53·0°	—	45°
33	700 ft	1·722	—	53·4°	—	—
35	600 ft	1·720	—	—	50·8°	42½°
39	330 ft	1·718	—	—	—	—
40	300 ft	1·724	—	—	51·0°	—

Dykes,

BM.1966, P5	Locality	RI(γ)		$2V_\gamma$ (mean value)		$\gamma \wedge C$
		Phenocrysts	G-mass	Phenocrysts	G-mass	
82–83	Blinkenthorpe beach	—	1·733	53·2°	48·2°	—
95–97	Rabbit Island	—	1·735	52·2°	—	44° (microphenocryst) 45½° (g-mass)
55, 59, 66, 70, 71	North beach	1·717, 1·719	1·730	52·1°	50·2°	45½° (g-mass)
102	Admiralty Islets	1·719	—	52·5°	—	45° (g-mass)
76, 79	Ned's beach	—	1·734	52·0°	—	—
98, 100, 101	Quarry near lagoon	—	1·733	52·9°	48·6°	43½° (microphenocryst) 46° (microphenocryst)
89, 91, 92, 93	Middle beach	1·720	1·732	52·3°	48·5°	47° (g-mass)

are no variations that exceed experimental error in either groundmass or phenocrysts. Table IV shows the mean optical values for both lavas and dykes combined.

The range in values of the γ index for phenocrysts and for groundmass pyroxenes is given in Text-fig. 8 whilst Text-fig. 9 shows the corresponding range in 2V. Text-fig. 10 emphasizes the similarity between lava and dyke phenocrystal pyroxenes as regards their 2V values.

TABLE IV

MEAN OPTICAL VALUES FOR PYROXENES

	Groundmass pyroxene	Phenocrystal pyroxene
$2V(\gamma)$	49·2°	52·8°
γ	1·734	1·720
$\gamma \wedge C$	45½°	44½°

Since the optical properties show that all pyroxene phenocrysts (from both lavas and dykes) have virtually identical compositions, and that the same is true for the groundmass pyroxenes, analysis of a pyroxene from each generation should suffice to represent the composition of all pyroxenes from that generation in both lavas and dykes. A dyke (BM.1966, P5, 66) from North beach was used for separation and analysis of groundmass pyroxenes, while an oceanite-ankaramite (BM.1966, P5, 33) from a height of 720 ft in the Gower-Lidgbird sequence was taken for separation and analysis of phenocrystal pyroxene.

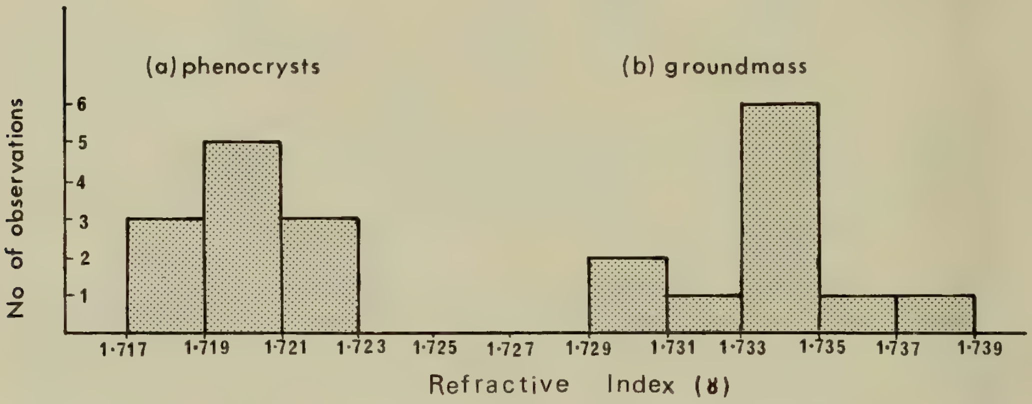


FIG. 8. Range in refractive index (γ) values for (a) phenocrystal pyroxenes and (b) groundmass pyroxenes (Gower-Lidgbird lavas and dyke rocks combined).

The analyses of these two pyroxenes are shown in Table V together with the values of γ, 2V, and of the cell sides and the angle β. In the triangular diagram (Text-fig. 11) the composition, derived from analysis, is compared with the composition derived from X-ray measurements of cell sides and of β. The augite phenocrysts from Lord Howe Island, though slightly richer in magnesium and poorer in calcium, match, closely, those from a picrite basalt from Gough Island (LeMaitre, 1962). Moreover the trend in the compositional range between phenocrysts and groundmass is very similar to the initial trends plotted for alkali basalt pyroxenes in general, i.e. it is parallel to the Di-Hd join, the molecular calcium percentage remaining constant with increase in iron. In tholeiitic pyroxenes, by contrast, the initial trend

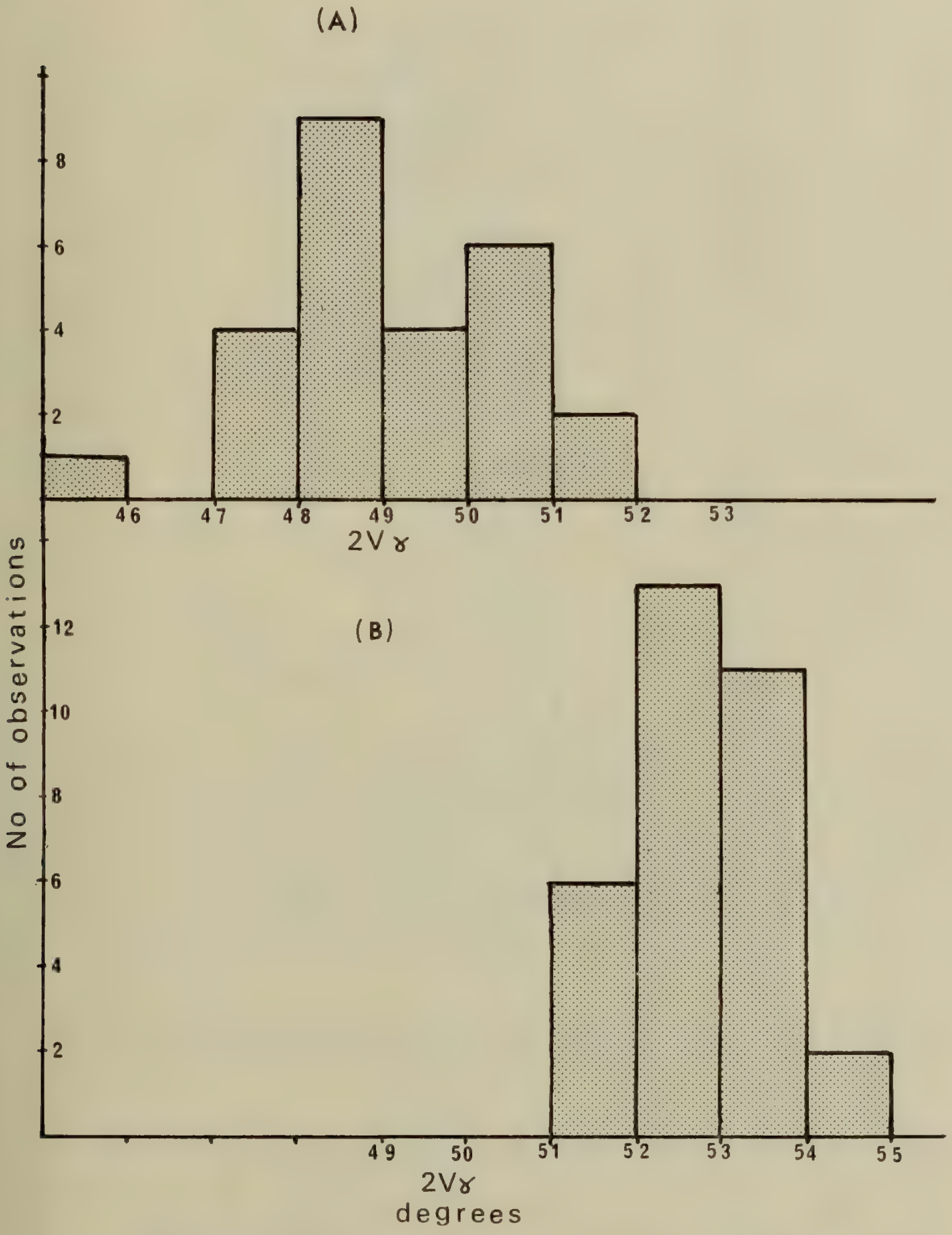


FIG. 9. Range in optic axial angles in (A) groundmass and (B) phenocrystal pyroxenes.

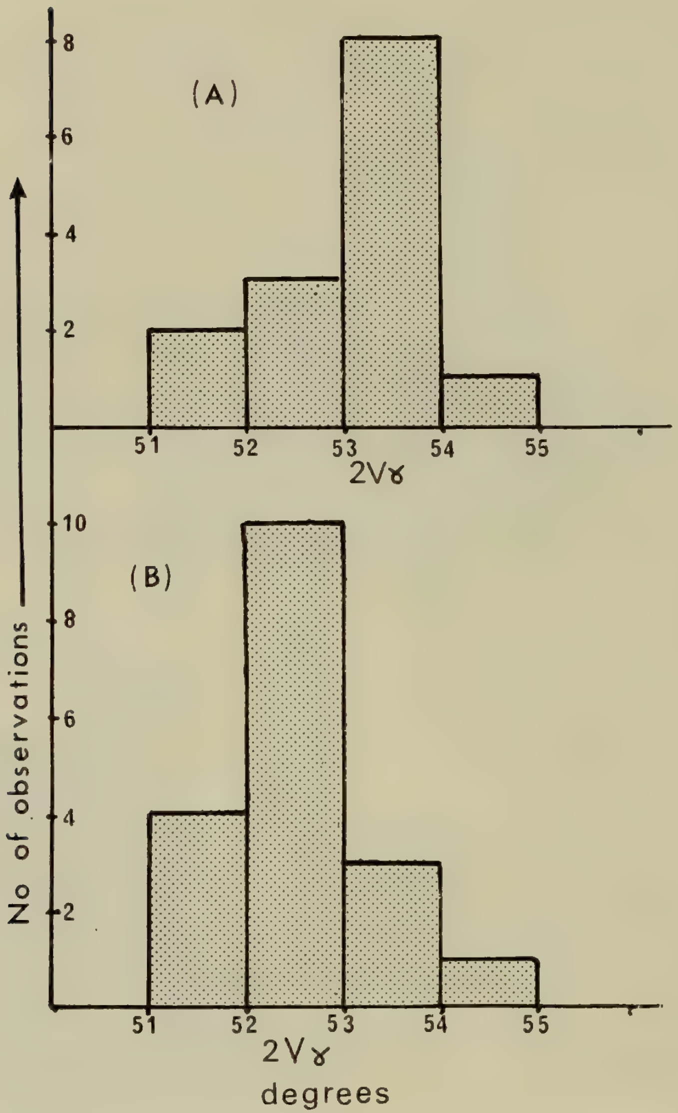


FIG. 10. Range in optic axial angles in pyroxene phenocrysts in (A) The Gower-Lidgbird lava series and (B) The dyke rocks.

is one of impoverishment of calcium as well as of enrichment in iron (LeMaitre, op. cit.).

The slight deviations, in the same sense, between the Ca : Mg : Fe ratios determined by chemical analysis on the one hand and by X-ray analysis on the other may be due to the relatively large amount of aluminium in these pyroxenes, and especially to the Al in 6-fold co-ordination. Although the Al allotted on the formal

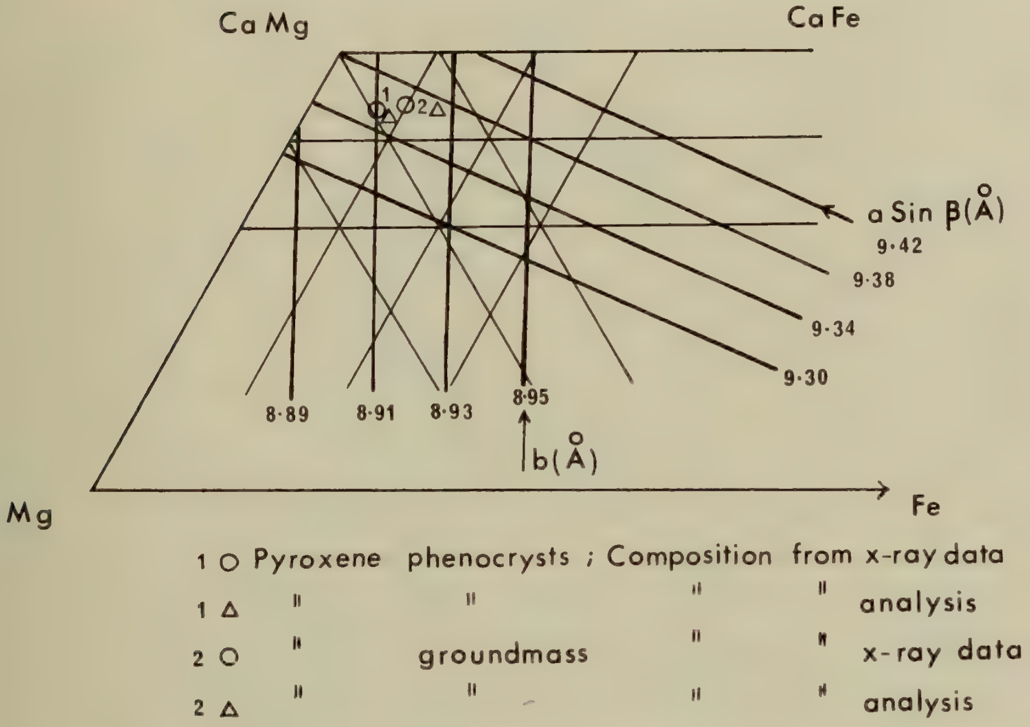


FIG. 11. Pyroxenes ; comparison of chemical and X-ray data.

6-oxygens basis of the analyses is 0·047 for the phenocryst and 0·036 for the groundmass there is, of course, no method for apportioning the total Al between the Al_6 and Al_4 sites. According to Brown (1960) the critical value of Al_6 which the pyroxenes can accommodate without alteration of cell is 0·05. A surplus causes a reduction in the value of b. As such a reduction can be observed to have occurred in both analysed pyroxenes from Lord Howe Island it seems reasonable to assume that more Al occurs in 6-fold co-ordination than the amounts derived formally from the analyses—in which case some Ti might possibly go into the Z position to preserve the necessary balance.

The relations between the compositions derived from the optical parameters γ and 2V and those obtained from the analyses are shown in Text-fig. 12. This shows that the compositions derived from the optics are at considerable variance with the analytical compositions. The discrepancy is almost entirely due to the refractive index values, which are as much as ·015 to ·020 too high, when interpreted on Hess' (1949) diagram. This diagram was used because Hess plotted the γ index which was the index measured on the Lord Howe Island pyroxenes. If the most recent diagram (Brown and Vincent, 1963) is used and if $\gamma - \beta$ is taken as ·02 then the discrepancy is slightly reduced, but is still just over ·01 for the phenocrystal pyroxene (in which the refractive index may be assumed to have been accurately measured). It should

TABLE V

ANALYSES OF PYROXENES (Analyst : A. A. Moss)

	Pyroxene phenocryst BM.1966, P5, 33	Pyroxene groundmass BM.1966, P5, 66	Number of ions on the basis of 6 oxygens				
				BM.1966, P5, 33		BM.1966, P5, 66	
SiO_2	50·3	49·3	Si	1·844	2·00	1·838	2·00
TiO_2	1·0	1·6	Al	0·156		0·162	
Al_2O_3	4·7	4·5	Al	0·047	2·03	0·036	2·01
Fe_2O_3	0·9	2·5	Ti	0·028		0·045	
FeO	5·4	7·6	Fe^{3+}	0·025		0·070	
MnO	0·1	0·1	Fe^{2+}	0·165		0·237	
MgO	17·1	14·0	Mn	0·003		0·003	
CaO	20·4	19·6	Mg	0·934		0·778	
Na_2O	0·33	0·76	Ca	0·801		0·783	
K_2O	0·05	0·11	Na	0·023		0·055	
			K	0·002		0·005	
Total	100·28	100·07					

Optical data

	BM.1966, P5, 33	BM.1966, P5, 66
$2V\gamma$	52·7°	49·2°
γ	1·722	1·733

X-ray data

	BM.1966, P5, 33	BM.1966, P5, 66
a	9·747 Å	9·757 Å
b	8·909 Å	8·917 Å
c	5·266 Å	5·274 Å
β	106·334°	106·331°

be noted that Deer and Abbott (1965) obtained the same orders of difference and in the same sense, between the expected and the measured refractive indices for clinopyroxenes from gabbro cumulates in east Greenland, for which the total Al and the Ti percentages are similar to those of the Lord Howe Island pyroxenes. As these authors remark " data bearing on the relative effects of tetrahedrally and octahedrally co-ordinated Al on the refractive index of clinopyroxenes is both scanty and conflicting ". They consider " the b and a sin β parameters are superior to the β index and 2V as a guide to composition ", with which opinion the author is in complete agreement.

Zoning of pyroxenes. This occurs in both phenocrysts (Pl. 12, 3) and groundmass although it is never intense. It is more common in the dykes than in the flows. In the dykes determinations of 2V on the cores and on the exteriors of pyroxenes showed that 2V is, on the average, 3·0° greater for the cores of phenocrysts than it is for their margins (mean values are 52·7° and 49·7° respectively). For the groundmass 2V is 3·5° greater at the centre than it is at the exteriors (50·4° against 46·9°). A difference of 3° to 3½° in 2V suggests that the calcium molecular percentage is about 3% lower at the margins. Having regard to the fact that the optical-chemical relationships for monoclinic pyroxenes are not well established, a microprobe analysis was made on a zoned crystal from a dyke (BM.1966, P5, 96) from Rabbit Island.

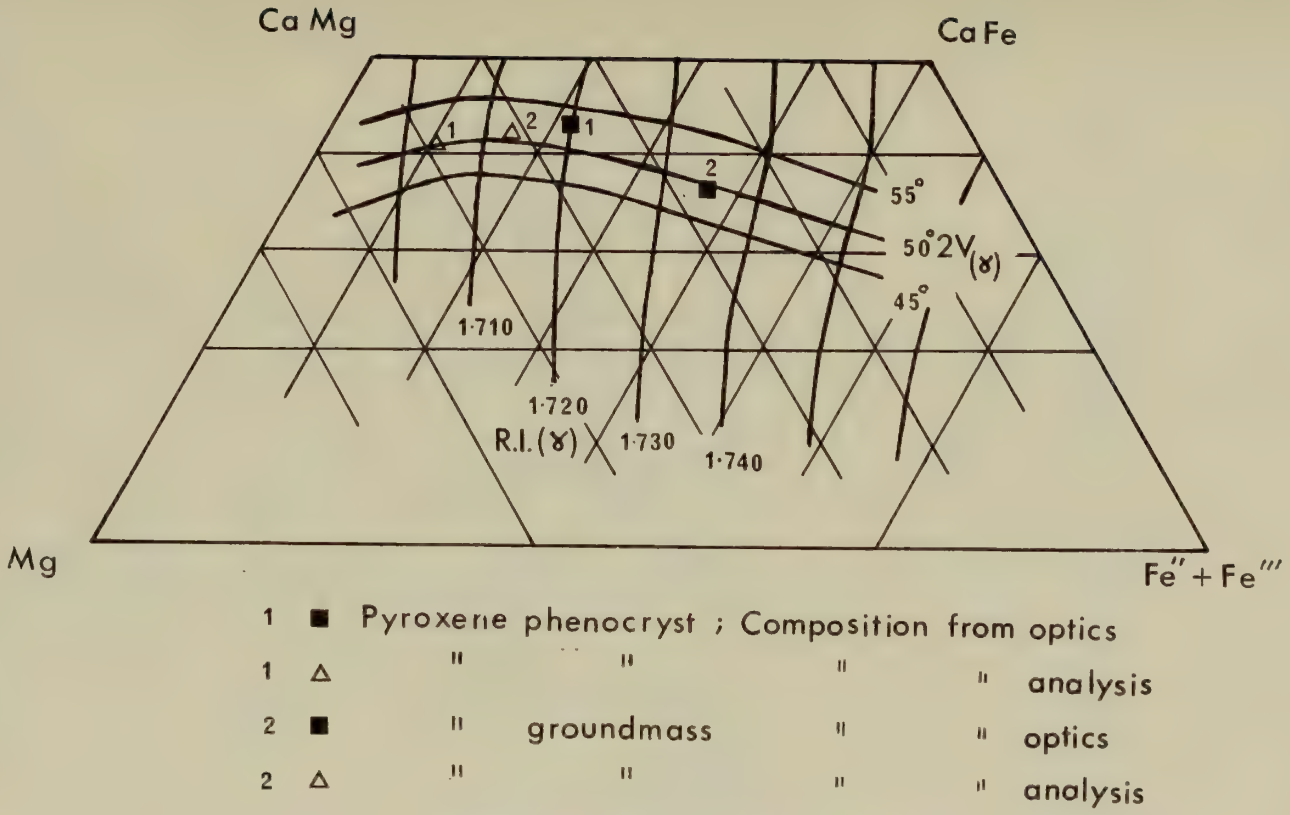


FIG. 12. Pyroxenes ; comparison of chemical and optical data.

Approximately 25 measurements were made on the margin and on the centre. The results, in weight percentages of elements (Fe includes ferrous plus ferric iron) were :

Centre : Fe 6·60 Ca 15·17 Si 22·62 Mg 9·61 : $\frac{\mathrm{Mg}}{\mathrm{Fe}} = 1{\cdot}46$

Margin : Fe 7·02 Ca 15·29 Si 22·14 Mg 8·50 : $\frac{\mathrm{Mg}}{\mathrm{Fe}} = 1{\cdot}21$

It is significant that these analyses show no appreciable change in calcium ; at the periphery however iron is higher and magnesium is lower.

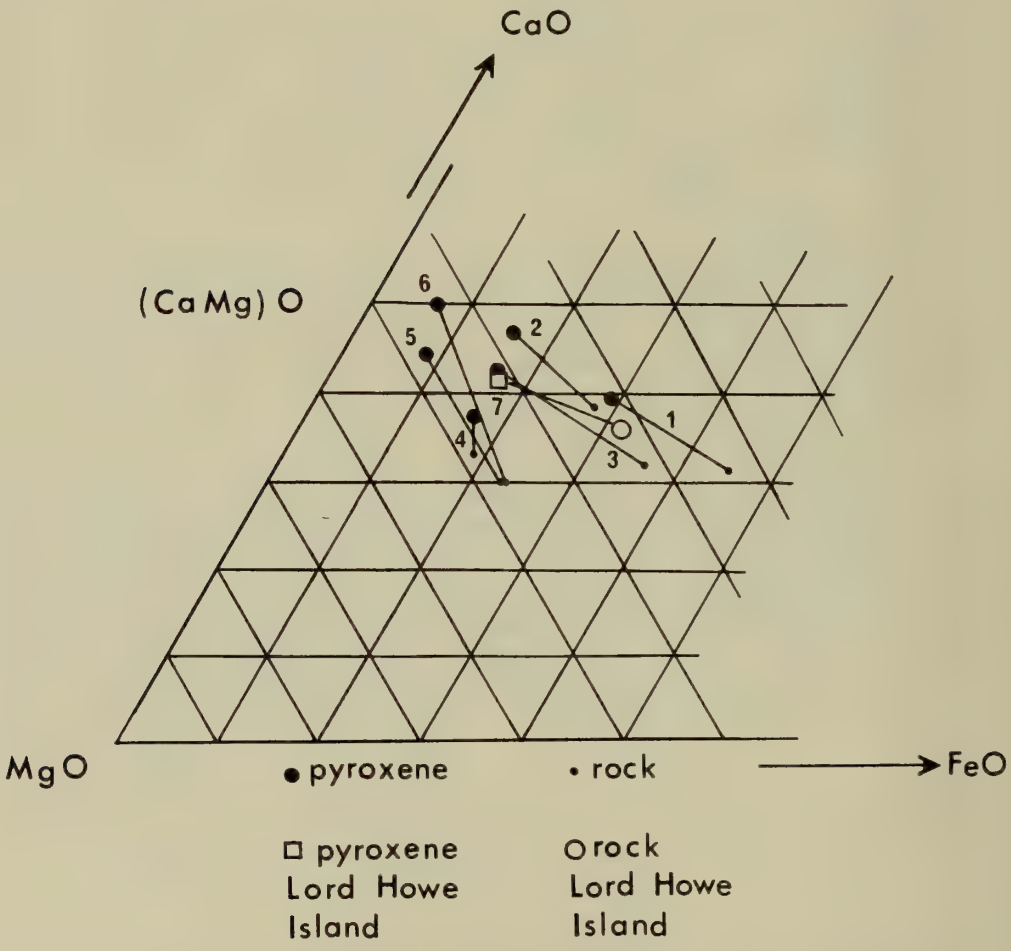


FIG. 13. Pyroxenes of olivine-basalt magmas in relation to the rocks in which they occur ; after W. Q. Kennedy (1933). 1. Satakunta, Finland. 2. Magdesprung, Hartz. 3. Mount Taylor region, New Mexico. 4. Azores. 5. Etna. 6. Hawaii. 7. Lord Howe Island.

Text-fig. 13 shows that the pyroxene which separates from the Lord Howe Island magma is richer in lime than the magma itself. In this it accords with pyroxenes from olivine-basalt magmas in general, six of which are reproduced from Kennedy (1933).

(*d*) Olivines

Olivine occurs as phenocrysts in all the porphyritic lavas of the Gower-Lidgbird series. It is completely unaltered in two flows, although in a further two the alteration is very slight. In the great majority of the remaining lavas of this sequence phenocrystal olivine is iddingsitized to greater or less extent. In most instances only the periphery is affected (Pl. 11, 3) but in a few instances almost the whole crystal has been iddingsitized. In three flows from the middle of the sequence (BM.1966, P5, 24, 26 and 27) and in one from the base (BM.1966, P5, 40) olivine phenocrysts are serpentinized. In one of these flows (BM.1966, P5, 26) the alteration is very slight.

In the groundmass of the Gower-Lidgbird lavas olivine occurs in most of the flows, but it is more abundant in the lower part of the sequence (300 to 1500 ft) than it is in the upper part (1500–2800 ft).

Olivine phenocrysts also occur in some of the dykes, but they are much less plentiful than in the flows. As previously stated olivine only occurs significantly in 8 dykes out of the 52 examined. (In a further 2 dykes it is very sparse.) Five of these 8 dykes are rich in olivine phenocrysts. They include two dykes from the Admiralty Isles, and one each from Middle beach, Ned's beach, and the quarry by the lagoon. Olivine occurs sparingly in the groundmass in only six dyke rocks, all of which are among those carrying olivine phenocrysts. In the dykes the olivine is always serpentinized (never iddingsitized) to a greater or less degree (Pl. 11, 2). In some rocks, e.g. BM.1966, P5, 78 from Ned's beach and BM.1966, P5, 102 from the largest Admiralty Isle, the crystals are only very slightly altered along cracks. In others, e.g. BM.1966, P5, 71, from North beach and BM.1966, P5, 99 from the quarry near the lagoon, serpentine sometimes completely pseudomorphs original olivine.

Composition. The compositions of the olivines were derived from the refractive index values determined by the single variation method. Text-fig. 14 shows the composition of the olivines from the Gower-Lidgbird lavas and from the dykes. In the lavas the composition of the olivine phenocrysts shows no significant variation in the flows of the upper 1300 ft, where it averages 26% (molecular) of Fe_2SiO_4. In the lower 1500 ft (i.e. in those flows which also carry more olivine in the groundmass) the composition of the phenocrystal olivine shows minor, albeit abrupt, variations from 18% to nearly 28% Fe_2SiO_4. The average composition is 23% in this lower part of the sequence. As the diagram shows there is a slight but definite trend towards enrichment in iron from the base of the series to a point about half way up. Groundmass olivine could only be accurately determined from two flows (at about 1500 ft) from which a mean value of 36% Fe_2SiO_4 was obtained. Since the phenocrysts of these particular flows have a composition of 21% Fe_2SiO_4, the groundmass olivine has 15% more Fe_2SiO_4 than the phenocrysts. A third flow

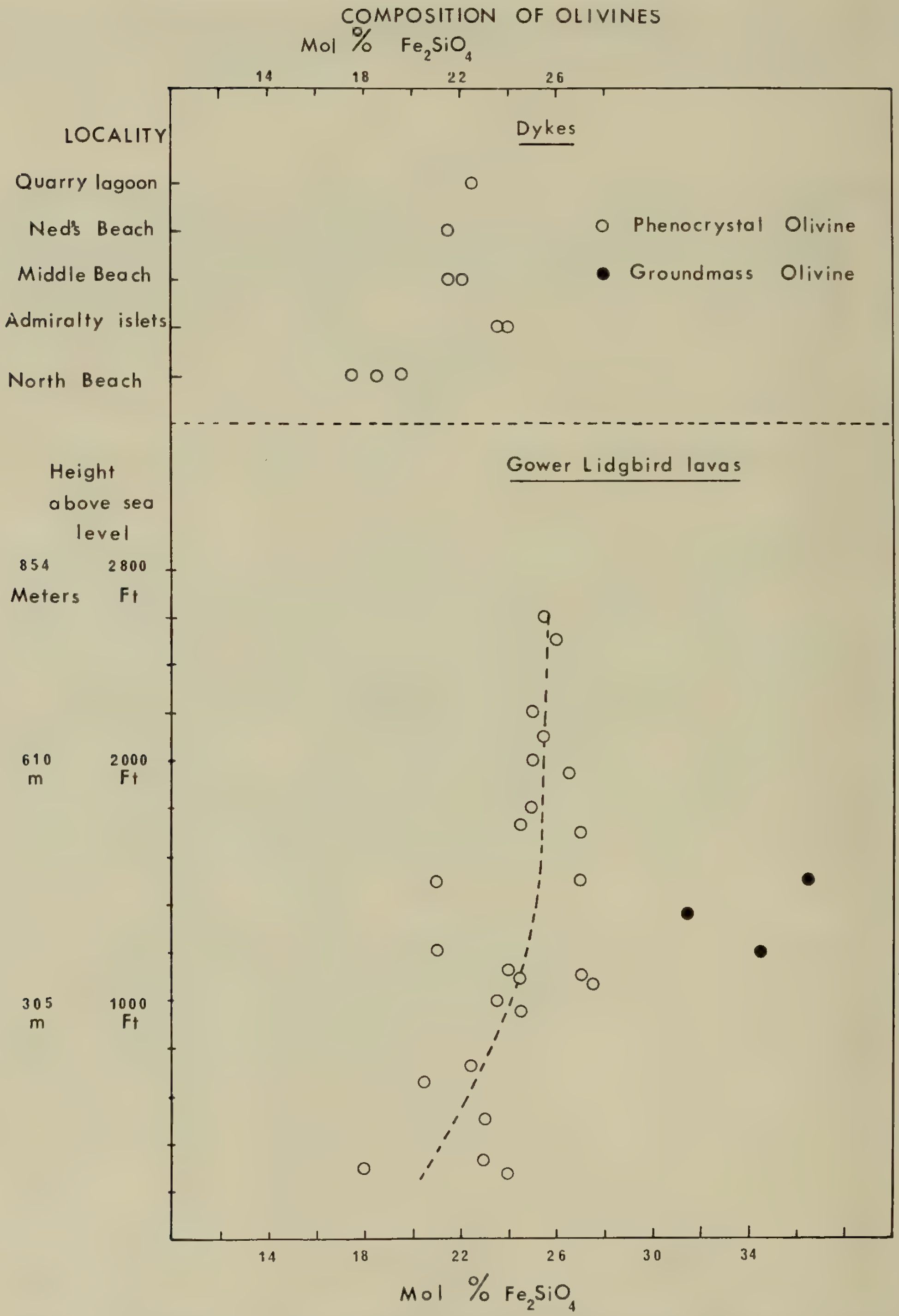


FIG. 14. Composition of olivines from the Gower-Lidgbird series and from the dykes.

(1370 ft) with very small phenocrysts has olivine of an intermediate composition between groundmass and phenocrysts.

In those dykes with phenocrystal olivine, the composition of the latter ranges from 17½% to 24% Fe_2SiO_4. Iron is lowest in the olivines of the dykes from North beach, four of which carry olivine phenocrysts, with a mean composition of 18% Fe_2SiO_4. Olivine phenocrysts from all other olivine bearing dykes have a mean composition of 22½% Fe_2SiO_4. This difference in composition (4½% Fe_2SiO_4) is outside the limits of experimental error and must be regarded as significant. With the exception of the North beach dykes, the mean composition of the olivine phenocrysts of the dyke rocks is thus virtually identical with the mean composition of phenocrystal olivines from the lower part of the Gower-Lidgbird lava sequence.

(*e*) Iron Ores

The ores, which are of universal occurrence in both lavas and dykes were examined by means of the microprobe. Total Fe and Ti weight percentages were obtained. The results for the lavas and dykes are plotted in Text-fig. 15. The ores fall into two groups ; the first is close to theoretical ilmenite, while the other appears to approximate to a Ti-poor Fe-rich ulvöspinel.

The points show considerable scatter and much of this is undoubtedly due to the practical difficulties of resolution with the probe on such small particles. There is

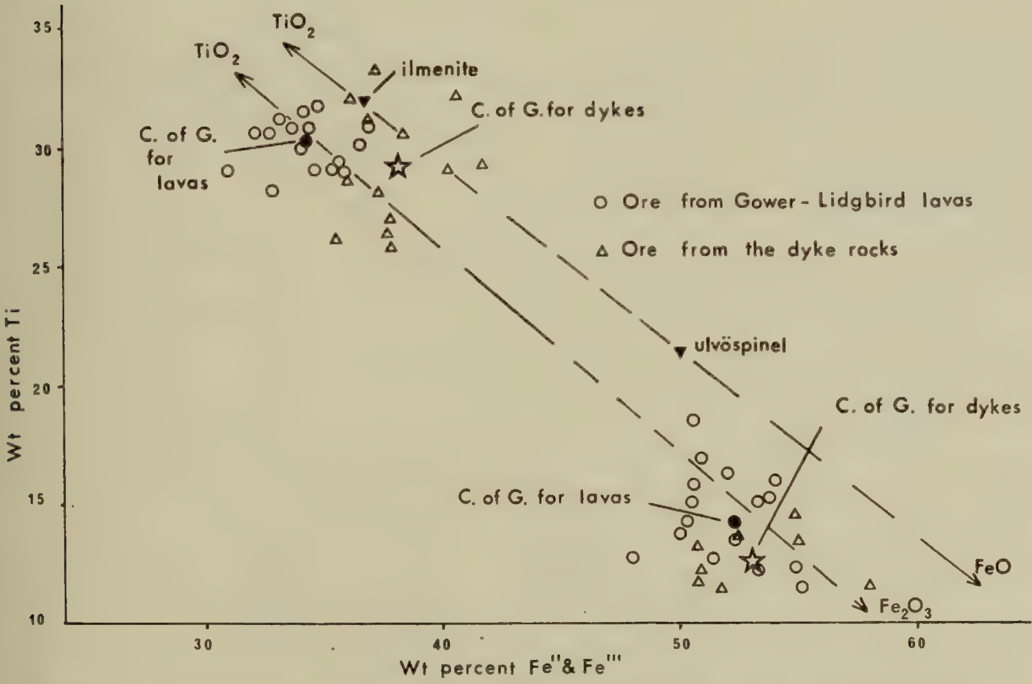


FIG. 15. Iron–titanium ratio for lavas of the Gower-Lidgbird sequence and for the dyke rocks.

almost certainly a systematic error (in addition to the random scatter), for a considerable number of points plot outside the TiO_2-Fe_2O_3 join in the TiO_2-Fe_2O_3-FeO triangle. In these Fe and Ti are deficient and there is too high a proportion of oxygen. This may possibly be due to the traverse by the beam of silicates in addition to the ores.

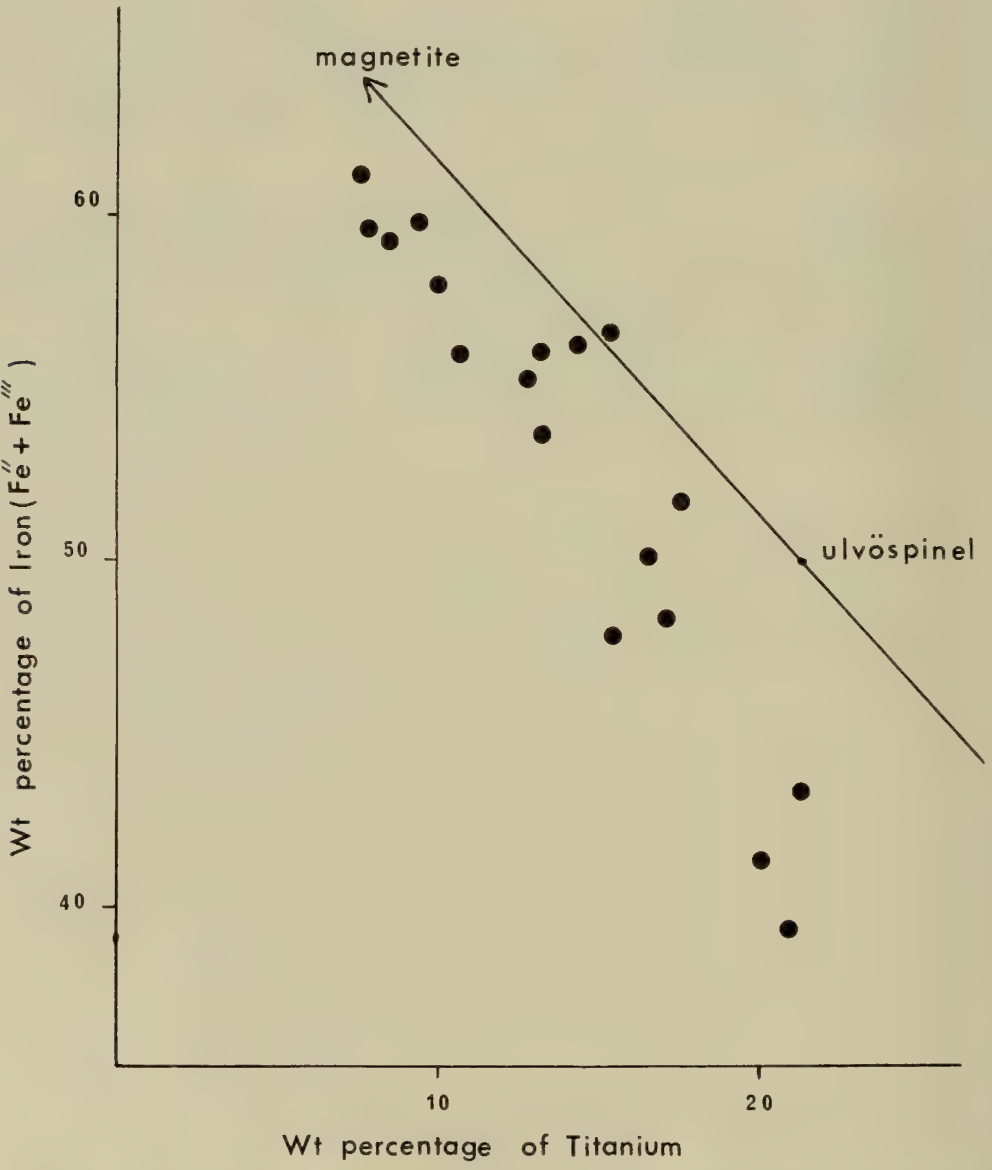


FIG. 16. Iron–Titanium ratios for individual ore grains in flow BM.1966, P5, 28 at 1100 ft above sea level.

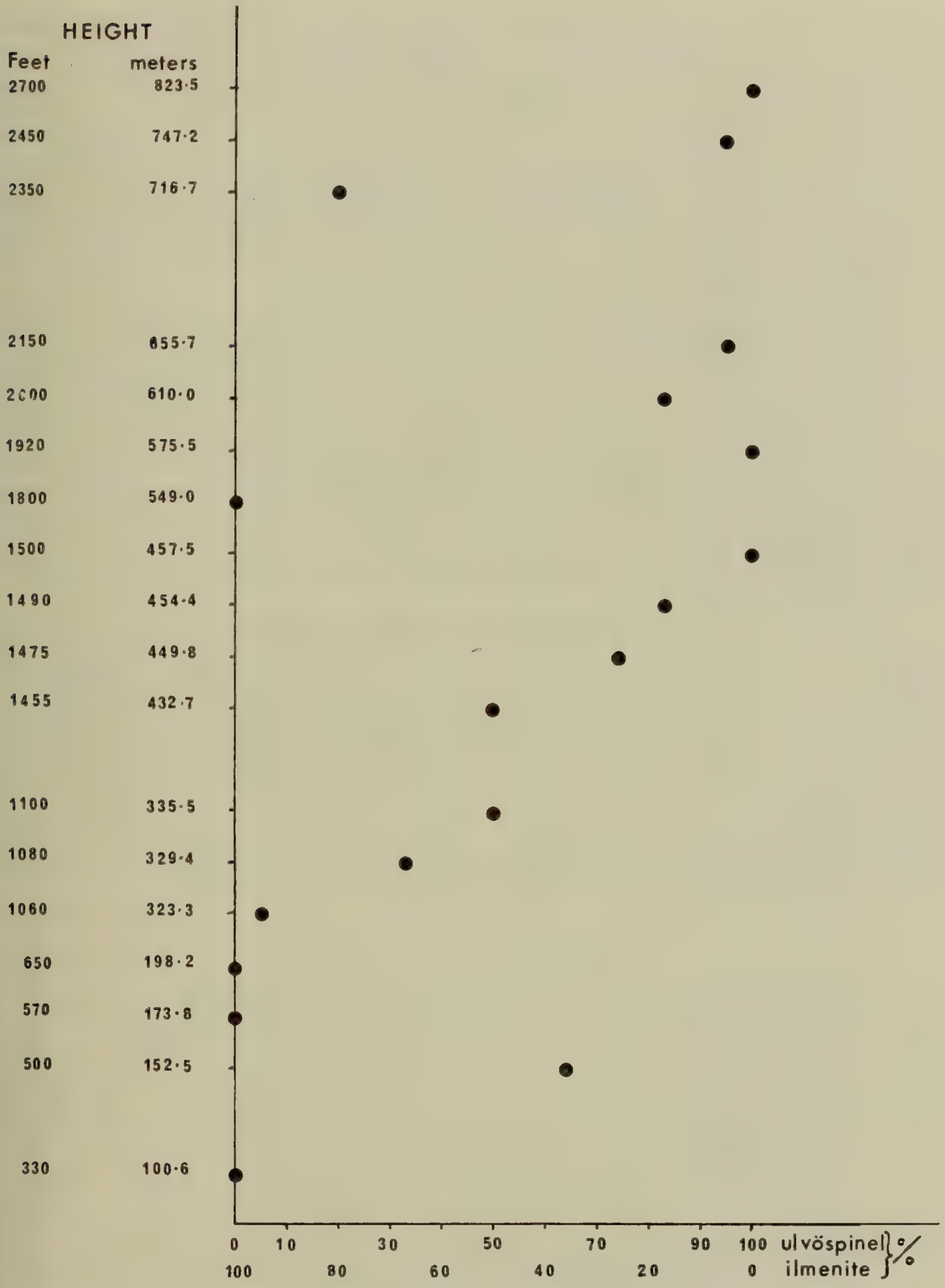


FIG. 17. Relation between height of flow above sea level and type of ore, Gower-Lidgbird series.

In spite of the scatter and probable " translations " approximately perpendicular to the ilmenite-ulvöspinel join, of the centres of gravity of the groups it seems reasonable to postulate a small difference in composition between the ilmenites of the dykes and those of the lavas. The former have on average 4% more Fe and 1% less Ti than do the latter. The dyke ilmenites have begun to move along the ilmenite-haematite solid solution join with cooling and oxidation, but are still close to theoretical ilmenite. The ilmenites of the Gower-Lidgbird lavas do not show this trend, but appear to be more affected by the systematic error mentioned above and their centre of gravity is near the TiO_2-Fe_2O_3 join. Nevertheless both their Fe and Ti percentages are still within 3% of those of ilmenite.

In the Ti-poor ulvöspinel group no significant difference between the ores of the lavas and of the dykes can be detected. It is probable that the first ore to form was an ulvöspinel of the ulvöspinel-magnetite solid solution ; with cooling and oxidation this early crystallized ore would move towards the magnetite end of this solid solution series, possibly with exsolution of lamellae of ilmenite. That this does occur in some instances can be seen by reference to Text-fig. 16 in which the Fe and Ti percentages of individual grains from a fine-grained lava (BM.1966, P5, 28, 1100 ft a.s.l.) have been plotted. The trend of the resulting points is close to that of the magnetite-ulvöspinel join. It is also interesting to note with reference to this diagram that the Mg percentage, which varies from 0·4% to 2·0% is directly proportional to the percentage of Ti.

In the Gower-Lidgbird series there is a definite trend from ilmenite bearing flows in the lower layers to ulvöspinel bearing lavas near the top. The plot (Text-fig. 17) shows that the lowest flows (with one exception) have only ilmenite, while the upper flows (again with one exception) have only ulvöspinel. The lavas near the middle of the series contain both types of ore (again with one exception, BM.1966, P5, 16 from 1800 ft), which has only ilmenite. The dyke rocks contain both ilmenite and ulvöspinel but the proportion varies greatly. Three dykes at North beach contain an average of 34% ulvöspinel, in contrast with an average value of 83% ulvöspinel for three dykes from other localities. But more determinations would be needed to test the occurrence of any relation between locality and type of ore.

IV. BULK CHEMICAL ANALYSES

The results of fourteen chemical analyses (9 flows and 5 dyke rocks) are given in Table VI, and Table VII shows the molecular norms. In the absence of sufficient felsic variation it is not possible to construct an alkali-lime index diagram, but the triangular diagram for magnesia, iron oxides and alkalis is shown in Text-fig. 18. The K_2O, Na_2O, CaO triangular diagram is also shown in this figure. Text-fig. 19 shows the relation between Al_2O_3 and total alkalis. Here the Lord Howe Island rocks are compared with basaltic types from the Circum-Japan sea province (see Kuno 1959) and with Nockolds' (1954) " normal alkali basalts " and " average alkali andesites ". This shows that nearly all the Lord Howe Island basalts fall within Kuno's alkali basalt group. In spite of the small corundum content in the norm of two Lord Howe Island basalts, none approaches Kuno's high alumina basalt group. The figure also demonstrates a close conformity between the Lord Howe

TABLE VI

ANALYSIS OF GOWER-LIDGBIRD LAVAS AND OF YOUNGER DYKE ROCKS (Analyst : J. EASTON)

	Lavas (Gower-Lidgbird sequence)									Dykes				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	48·3	44·5	44·5	49·6	47·5	46·0	48·5	49·1	48·3	49·6	46·3	48·9	46·3	46·4
TiO_2	2·3	2·6	1·8	2·3	3·3	2·8	2·4	3·0	3·2	2·6	2·4	2·6	2·2	2·4
Al_2O_3	16·5	13·3	10·6	18·1	14·6	14·5	14·5	15·3	15·4	14·2	14·7	13·9	13·0	15·5
Fe_2O_3	3·6	3·5	5·1	2·9	4·1	6·4	3·4	6·9	3·0	2·7	2·6	6·2	1·9	2·1
FeO	7·8	8·4	8·7	8·4	7·6	5·9	6·8	5·2	7·3	8·0	7·0	5·0	9·2	9·0
MnO	0·13	0·15	0·14	0·13	0·14	0·15	0·16	0·16	0·17	0·14	0·17	0·16	0·18	0·18
CaO	4·5	8·7	7·5	5·4	8·5	8·9	7·9	8·5	9·3	9·7	10·3	8·7	8·2	8·3
MgO	5·0	11·8	17·0	3·9	7·1	8·0	7·9	4·7	4·3	4·8	5·6	5·8	12·2	9·5
Na_2O	5·0	2·0	1·9	5·2	3·5	3·0	3·5	3·6	3·7	3·3	3·5	4·1	2·3	2·5
K_2O	2·1	1·1	0·6	1·8	1·9	1·3	1·7	1·3	1·5	1·2	0·6	1·0	1·1	1·1
Cr_2O_3	0·01	0·05	0·10	0·01	0·03	0·04	0·05	0·01	0·02	0·07	0·09	—	0·21	0·10
P_2O_5	0·83	0·48	0·23	0·39	0·53	0·48	0·54	0·54	0·58	0·36	0·30	0·42	0·40	0·41
CO_2	<0·1	0·2	0·2	<0·1	0·2	0·2	0·3	0·2	<0·1	0·2	4·8	0·4	0·2	0·2
H_2O^+	3·2	2·9	2·0	1·4	1·1	2·2	2·3	1·2	2·7	3·0	1·0	1·0	2·1	1·4
H_2O^-	0·1	0·2	0·1	0·1	0·1	0·1	0·1	0·2	0·1	0·1	1·0	2·3	0·9	0·7
Total	99·37	99·88	100·47	99·63	100·20	99·97	100·05	99·91	99·57	99·97	100·36	100·48	100·39	99·79

1 Andesine basalt, Mt Gower, 2700 ft, BM.1966, P 5, 1.
2 Alkali olivine basalt, Mt Gower, 2600 ft, BM.1966, P 5, 2.
3 Oceanite, Mt Gower, 2200 ft, BM.1966, P 5, 8.
4 Trachybasalt, Mt Gower, 1920 ft, BM.1966, P 5, 14.
5 Alkali andesite, Mt Lidgbird, 1455 ft, BM.1966, P 5, 22.
6 Alkali olivine basalt, Mt Lidgbird, 1210 ft, BM.1966, P 5, 26.
7 Alkali olivine basalt, Mt Lidgbird, 1120 ft, BM.1966, P 5, 27.
8 Andesine basalt, Mt Lidgbird, 300 ft, BM.1966, P 5, 37.
9 Andesine basalt, Mt Lidgbird, 270 ft, BM.1966, P 5, 40.
10 Alkali basalt, North beach, BM.1966, P 5, 64.
11 Alkali basalt (with primary carbonate) Blinkenthorpe beach, BM.1966, P 5, 83.
12 Alkali basalt, Ned's beach, BM.1966, P 5, 80.
13 Alkali olivine basalt, Admiralty Islets, BM.1966, P 5, 102.
14 Alkali olivine basalt, Middle beach, BM.1966, P 5, 89.

TABLE VII

NORMS (MOLECULAR BASIS) OF ANALYSED GOWER-LIDGBIRD LAVAS AND DYKE ROCKS

	Lavas										
	1		2	3	4	5	6	7	8		9
	(a)	(b)							(a)	(b)	
cal	—	—	0·6	0·6	—	0·6	0·6	0·8	0·6	0·6	—
ap	1·9	1·6	1·1	0·5	0·8	1·1	1·1	1·2	1·1	1·2	1·3
il	3·4	3·4	3·7	2·4	3·2	4·6	4·0	3·4	4·4	4·2	4·6
or	13·0	13·0	6·5	4·0	11·0	11·5	8·0	10·3	8·0	8·0	9·25
ab	42·8	27·5	18·5	17·0	44·5	30·0	28·0	32·0	33·5	33·25	34·5
an	17·0	27·2	24·75	18·25	17·0	18·5	22·6	19·1	22·25	22.35	22·0
c	—	—	—	—	1·5	—	—	—	—	—	—
mt	3·9	4·0	3·75	5·4	3·0	4·35	6·9	3·6	6·0	4·35	3·3
hm	—	—	—	—	—	—	—	—	0·9	—	—
di	—	2·0	11·8	12·6	—	15·4	14·4	12·0	13·0	12·8	17·6
hy	—	20·6	11·3	11·5	—	—	7·5	5·6	7·2	12·9	2·9
ol	15·8	—	18·0	27·75	17·5	12·75	6·9	12·0	—	—	4·5
ne	2·2	—	—	—	1·5	1·2	—	—	—	—	—
q	—	0·7	—	—	—	—	—	—	3·05	·35	—

	Dykes				
	10	11	12	13	14
cal	0·8	12·2	1·0	0·5	0·4
ap	0·8	0·5	1·1	0·8	0·9
il	3·8	3·4	3·8	3·1	3·4
or	7·5	4·0	6·0	6·5	6·5
ab	31·0	31·5	38·0	21·0	23·5
an	21·15	19·5	17·25	22·5	28·1
c	—	1·3	—	—	—
mt	3·0	2·7	6·3	2·2	2·4
hm	—	—	0·2	—	—
di	19·4	—	17·0	12·2	8·0
hy	11·6	21·4	8·5	9·5	9·8
ol	—	—	—	21·7	17·0
ne	—	—	—	—	—
q	0·95	3·5	0·85	—	—

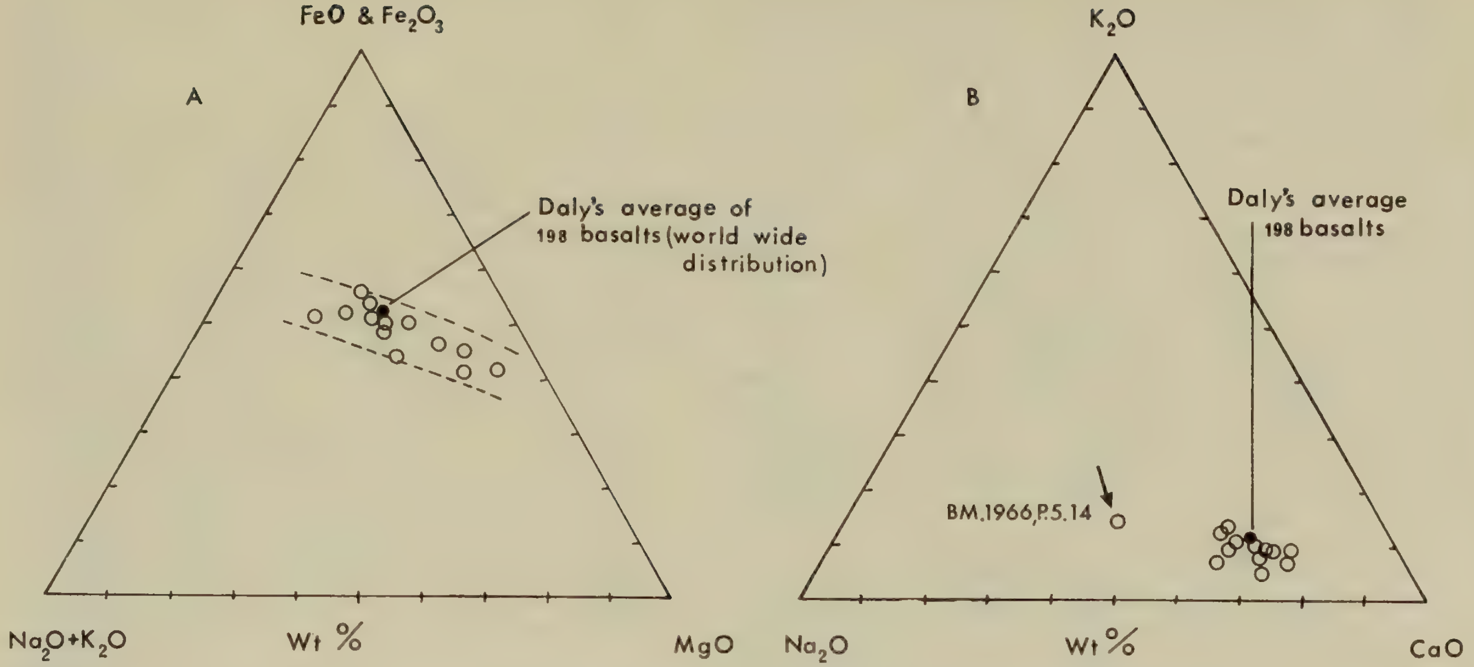


FIG. 18. Triangular variation diagrams for analysed basalts from Lord Howe Island. A : MgO–FeO–AlK. B : CaO–Na$_2$O–K$_2$O.

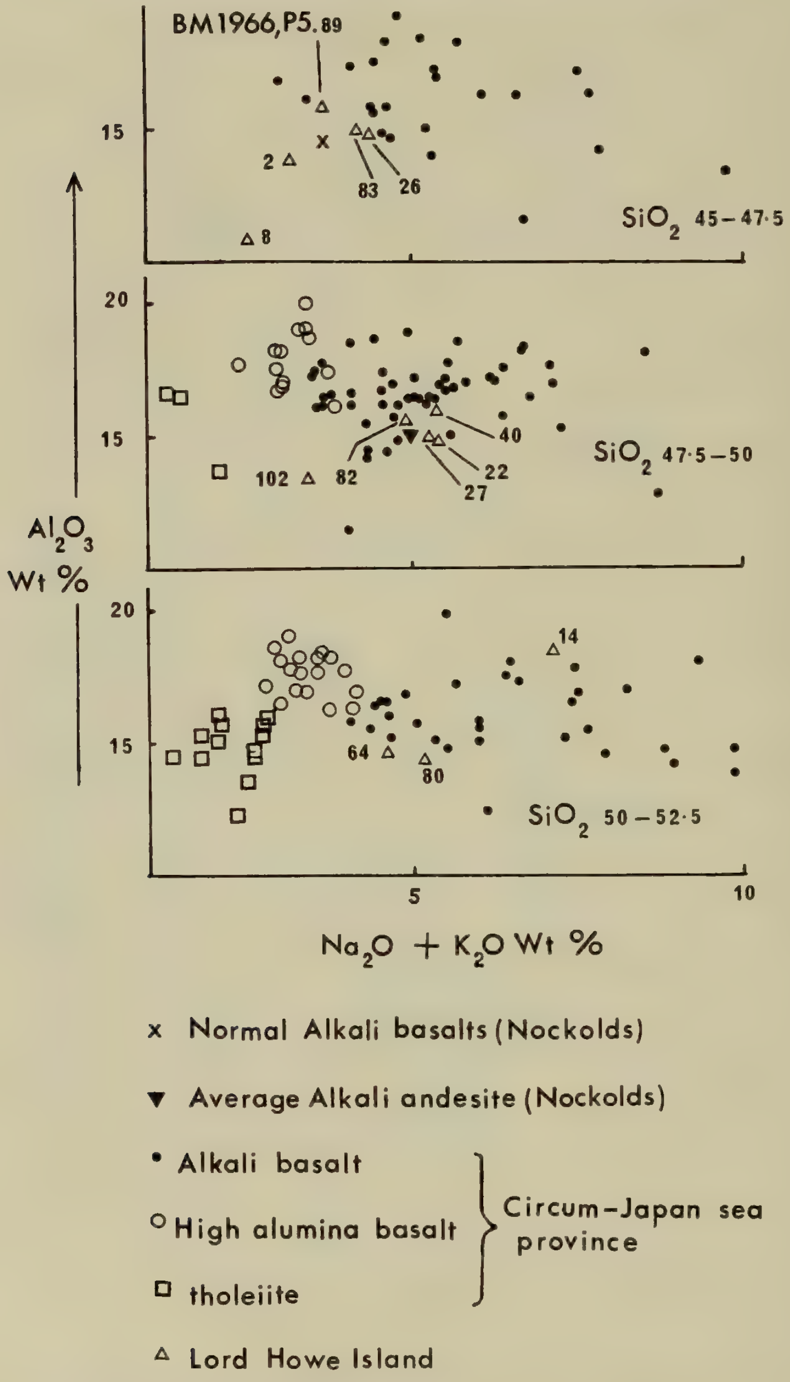


FIG. 19. Alumina—total alkali relationships for the Lord Howe Island basalts for varying SiO_2 percentages, compared with those of basalts from the circum-Japan sea province : *after H. Kuno.*

Island basalts and Nockolds' " average alkali andesite ". With regard to the Lord Howe analyses three points call for special mention ; first, in grouping the basaltic lavas for comparative purposes BM.1966, P5, 14 has been omitted because its field relations suggest that it is an inclined transgressive sheet (late differentiate) and not a flow. Second, the 2·2% of normative nepheline in the highest flow (BM.1966, P5, 1 norm 1a) is due to the albitization of the plagioclase in this flow (which is otherwise unaltered). Norm 1b for this rock shows the result of reallocation of the CaO and Na_2O in the mean proportions in which they occur in the Lord Howe Island lavas as a whole. This results in a very slightly oversaturated norm ($\frac{3}{4}$% quartz) instead of an undersaturated one. Third, the only lava to show normative quartz (BM.1966, P5, 37 norm "a") owes the 3% excess SiO_2 almost entirely to the unusually high state of oxidation of the iron. Re-apportionment of the total iron in this rock to accord with the mean FeO : Fe_2O_3 ratio for the remaining lavas reduces the 3% excess SiO_2 to a mere $\frac{1}{3}$% (norm " b "). The remaining lavas contain normative olivine, but only two, one of which is the transgressive sheet (BM.1966, P5, 14) already mentioned, show small amounts of normative nepheline. The unusually high H_2O+ content of both flows and dykes (mean $H_2O+ = 2{\cdot}0\%$) is probably due to the relative abundance of the zeolite chabazite as a late stage product (often infilling vesicles).

In order to determine whether there is any trend in the lavas in silica saturation or undersaturation the norms were recalculated after conversion of all Fe_2O_3 to FeO and Table VIII shows the resulting deficiency in SiO_2 after forming hypersthene, but before using excess hypersthene to form olivine.

TABLE VIII

GOWER-LIDGBIRD LAVAS ; RELATION BETWEEN HEIGHT OF FLOW AND SILICA DEFICIENCY

BM. No.	Height (ft)	SiO_2 deficiency
1966, P5		
2	2600	−9·7
8	2200	−14·6
24	1455	−10·0
26	1210	−9·2
27	1120	−7·6
37	300	−3·7
40	270	−4·8

BM.1966, P5, 1 has been omitted because of the albitization of the plagioclase, and BM.1966, P5, 14 has been left out for the reasons previously given. The table shows a general tendency towards increased SiO_2 undersaturation with height, although this trend is reversed in the highest flow. The trend towards undersaturation accords with the trend towards soda enrichment of the plagioclase with height that has already been described (Text-fig. 3).

Comparisons. Table IX shows the average composition of 8 lavas and 5 dykes (combined) from Lord Howe Island and gives the compositions of those lavas

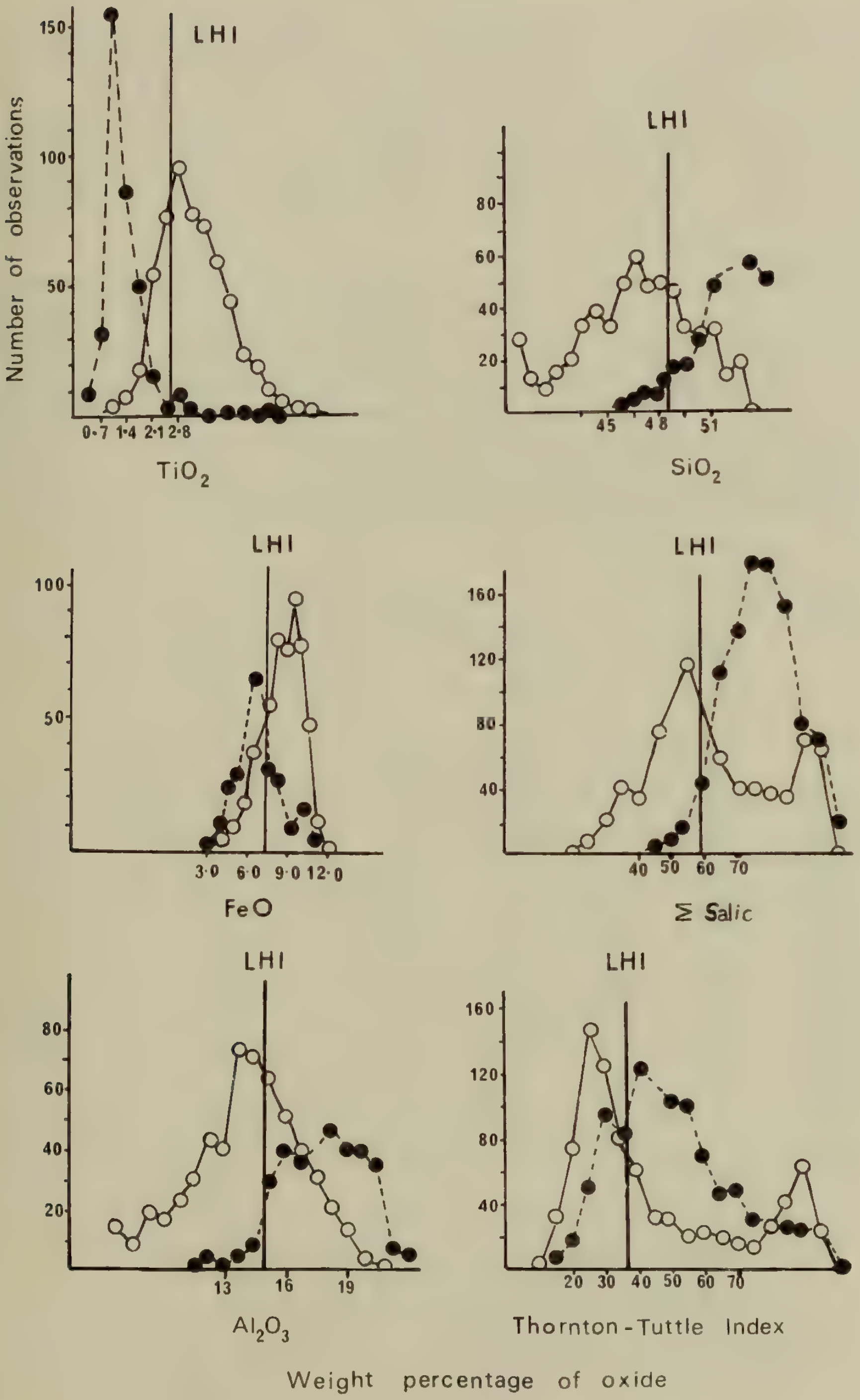
TABLE IX

COMPARISON OF AVERAGE LORD HOWE ISLAND BASALT WITH SIMILAR TYPES FROM OTHER LOCALITIES
(100% water-free basis)

	1	2	3	4	5	6
SiO_2	48·67	48·45	48·0	50·6	48·45	48·45
TiO_2	2·63	2·2	2·85	1·6	4·3	2·2
Al_2O_3	14·97	15·4	14·7	14·5	13·3	16·65
Fe_2O_3	3·99	3·9	4·0	4·3	4·05	3·35
FeO	7·67	8·05	7·9	7·1	8·3	7·3
MnO	0·16	0·15	0·2	0·2	0·15	0·2
CaO	8·66	9·5	9·55	8·6	7·7	9·5
MgO	7·87	7·25	7·3	8·4	8·2	6·05
Na_2O	3·33	3·3	3·8	2·9	3·45	3·5
K_2O	1·34	1·2	1·2	1·3	1·55	2·1
P_2O_5	0·46	0·6	0·5	0·4	0.55	0·7
CO_2	0·23	—	—	0·1	—	—
Cr_2O_3	0·02	—	—	—	—	—
			NORMS			
cal	0·6	—	—	0·1	—	—
ap	0·95	1·3	1·1	0·8	1·2	1·45
il	3·7	3·0	4·0	2·3	6·0	3·1
or	8·0	7·0	7·0	7·5	9·25	12·5
ab	29·75	29·75	29·75	25·5	31·25	24·0
an	22·0	23·75	19·5	23·4	16·25	23·15
c	—	—	—	—	—	—
mt	4·2	4·05	4·2	4·5	4·3	3·45
hm	—	—	—	—	—	—
di	13·2	15·8	19·6	13·2	14·8	17·2
hy	7·7	3·2	—	22·7	8·4	—
ol	9·9	12·15	12·15	—	8·55	10·8
ne	—	—	2·7	—	—	4·35
q	—	—	—	—	—	—

1 Lord Howe Island. Mean of 8 lavas and 5 dykes
2 Olivine basalts, East Otago, New Zealand : Benson (1946)
3 " Average alkali andesites " : Nockolds (1954)
4 Alkali basalts, Central Victoria, Australia : Edwards (1938)
5 Olivine basalts, Tutuila, Samoa : Daly (1927)
6 Basalt-trachybasalts, circum Japan Sea : Kuno (1959)

FIG. 20. Sample distribution (weight %) of TiO_2, SiO_2, Al_2O_3, FeO, and of Σ Salic and the Thornton-Tuttle index in oceanic Tertiary volcanics ; *after Felix Chayes 1964.* (Oceanic, solid line and open circles ; circum-oceanic, dashed line and solid circles.) The thick vertical solid line (LHI) shows the mean percentages of the named oxide and of Σ salic and the Thornton-Tuttle index for 15 analysed rocks from Lord Howe Island.


Number of observations
150
100
50
LHI
0·7 1·4 2·1 2·8
TiO2
LHI
80
60
40
20
45 48 51
SiO2
LHI
100
50
3·0 6·0 9·0 12·0
FeO
LHI
160
120
80
40
40 50 60 70
Σ Salic
LHI
80
60
40
20
13 16 19
Al2O3
LHI
160
120
80
40
20 30 40 50 60 70
Thornton-Tuttle Index
Weight percentage of oxide

that most closely match the Lord Howe average. It will be seen that the best matches are to be found among the New Zealand basalts (Benson, 1946) and in the " average alkali andesites " of Nockolds (1954) (probably mainly from the Hawaiian group). The alkali basalts from Victoria described by Edwards (1938) are also similar, but SiO_2 is a little higher and TiO_2 considerably lower. The Samoan olivine basalts, by contrast (Daly, 1927), have distinctly higher TiO_2 and $1\frac{1}{2}\%$ less Al_2O_3, but otherwise are fairly close to the Lord Howe Island average. In the Japan Sea province, K_2O is distinctly higher than in the Lord Howe Island group, but otherwise the match is good.

It is also instructive to compare the mean percentage of each oxide of the analysed rocks from Lord Howe Island with the distribution of this oxide weight per cent as given by Chayes (1964) for a large number of oceanic and circum-oceanic Tertiary volcanics. Text-fig. 20 shows Chayes' sample distributions. Although in all six distributions, the Lord Howe Island mean values fall close to the peak for the oceanic rocks, they are, in each instance, slightly displaced towards the circum-oceanic peak. The displacement is small, but the fact that it occurs in every instance is significant.

Close matches can also be found for the individual Lord Howe volcanics, Table X.

TABLE X

MATCHES FOR INDIVIDUAL LORD HOWE ISLAND ROCKS

	1	2	3	4	5	6	7	8
SiO_2	49·6	50·0	50·3	49·8	47·9	47·7	44·5	43·32
TiO_2	2·3	1·8	2·4	2·0	2·5	3·2	1·8	2·02
Al_2O_3	18·1	18·4	17·2	16·3	16·0	15·2	10·6	9·11
Fe_2O_3	2·9	4·2	3·8	2·9	2·2	2·3	5·1	4·94
FeO	8·4	6·8	8·1	8·6	9·3	8·7	8·7	8·42
MnO	0·13	0·05	0·1	0·3	—	—	0·14	—
MgO	3·9	3·3	5·2	5·4	9·8	9·7	17·0	17·02
CaO	5·4	6·7	4·7	8·2	8·6	8·9	7·5	9·28
Na_2O	5·2	4·8	5·2	3·2	2·6	2·7	1·9	1·86
K_2O	1·8	2·0	2·2	2·1	1·1	1·6	0·64	0·86
H_2O+	1·4	0·9	—	—	—	—	2·0	2·00
H_2O-	0·1	0·2	—	—	—	—	0·1	1·16
P_2O_5	0·39	0·34	0·8	0·4	—	—	0·23	0·34
CO_2	—	—	—	0·8	—	—	0·2	—
Totals	99·62	99·49	100·0	100·0	100·0	100·0	100·41	100·33

1 Lord Howe Island (BM.1966, P5, 14) ; trachybasalt ; Mt. Gower, 1920 ft.
2 Trachydolerite : St Helena ; Daly (1927)
3 Lord Howe Island (BM.1966, P5, 1) ; andesine basalt ; Mt. Gower, 2700 ft.
4 Andesine basalt : Victoria ; Edwards (1938)
5 Lord Howe Island (BM.1966, P5, 89) ; olivine basalt ; dyke, Middle Beach
6 " Basalt average " : Gough Island ; LeMaitre (1962)
7 Lord Howe Island (BM.1966, P5, 8) ; oceanite ; Mt. Gower, 2200 ft.
8 Ankaramite : Mauritius ; Walker and Nicolaysen (1953)

Thus BM.1966, P5, 14 the latest differentiate from Lord Howe Island, finds a close counterpart in a trachydolerite from St Helena, described by Daly (1927). The albitized lava (BM.1966, P5, 1) from the top of the Gower-Lidgbird sequence has an analysis which is close to the mean of certain andesine basalts from Victoria described by Edwards (1938). The albitization of the feldspar in the Lord Howe rock is shown in the table by the " reversal " of the CaO and Na_2O percentages, compared with those from the Victorian basalts.

Matches can also be found with basalts from other Atlantic islands. The analysis of an olivine basalt from a dyke at Middle beach, Lord Howe Island (BM.1966, P5, 89) can be compared with the " basalt average " as given by LeMaitre (1962) for Gough Island, in the South Atlantic.

The oceanites and oceanite-ankaramites of Lord Howe Island, typified by the analysed example BM.1966, P5, 8 from 2200 feet above sea level are matched by similar types from Mauritius (Walker and Nicolayson 1953).

It is likely that these Lord Howe Island oceanites (of which five examples were collected in 1700 ft of the Gower-Lidgbird sequence) were formed by the accumulation in basaltic magma of olivine (and much smaller amounts of pyroxene) phenocrysts. The oceanite contains 32% of olivine of composition $Fo_{74}Fa_{26}$. If this be subtracted from the bulk composition of the rock the remaining groundmass has a composition, as well as a norm, similar to some dyke rocks e.g. BM.1966, P5, 64 from North beach. There is consequently no necessity to postulate assimilation of CaO or any other material.

V. RELATION BETWEEN COMPOSITION AND DISTANCE FROM RIDGE CREST

The Niggli quartz number for the average Lord Howe Island basalt is $-25{\cdot}6$ and that for the trachyandesite (the most differentiated member) is -34.5. For basalts and their most differentiated products of islands near the East Pacific Rise or the Mid-Atlantic Ridge, McBirney and Gass (1967) have found a relation between the Niggli quartz number and the distance of the island from the crest of the ridge. In the eastern Pacific the curve for the basalts is almost flat over a distance of 5000 km. to the west of the rise and 2000 km. to the east. The mean value over this range is -25, virtually identical with that for Lord Howe Island. In the eastern Pacific, the latest differentiates have Niggli quartz numbers which for the most part are well above those for their parent magmas, whereas the reverse is true for Lord Howe Island and for the majority of the Atlantic islands. In the Atlantic ocean the curve for the Niggli quartz numbers of the islands to the west of the Mid-Atlantic Ridge shows a definite inclination. Here a value of $-25{\cdot}6$ (the 'average' Lord Howe basalt) indicates a distance from the ridge of 270 km., compared with the actual distance of Lord Howe Island from the crest of its Rise of 340 km. In the same region the value of $-34{\cdot}5$ (the most differentiated Lord Howe type) would correspond with a distance from the Ridge of 510 km. Thus the Lord Howe Niggli quartz numbers are of the same order as those of rocks that lie similar distances to the west of the Mid-Atlantic Ridge.

It should be noted that the Lord Howe Rise is now aseismic (Gutenberg and Richter, 1954) and in this respect it shows a marked contrast to the Mid-Atlantic Ridge and the East Pacific Rise, which are both more youthful structures with active vulcanicity. As Gutenberg and Richter remark, " Seismicity must have changed greatly in the course of geologic time—a few tens of thousands of years is ample time for extensive and significant changes in the local distribution of stress". Consequently the Lord Howe Rise may have been a seismic region up to the mid-Pliocene when vulcanicity ceased.

Van der Linden (1967) considers that the core of the rise was formed from an early Palaeozoic geosyncline. He concludes from the low angle unconformity on the north-east flank of the rise (discovered during a 1966 seismic survey by the " *R.V. Eltanin* ") that the crest of the rise was above sea level in the late Palaeozoic and early Mesozoic, and that it was the source of material for the New Zealand Permian and early Mesozoic sediments, which according to Fleming (1962) are derived from a landmass to the west.

Apart from the rather minor exception of the Ulladulla Trench which lies about 100 miles from the south eastern Australian coast, and is about 700 miles in length and about 17000 ft in depth, there is no trench off the east Australian coast, but a vast region 2000 miles wide between east Australia and the Tonga Trench which Chayes (1965) includes in his " shallow sea " or " Mediterranean " category. Lord Howe and Norfolk Islands are the only islands in this region, and exemplify Chayes' concept that " where the continent-ocean border is not marked by a Cenozoic trench, Cenozoic volcanics are not likely to be abundant and those which do occur are likely to be petrographically oceanic ". Although, as shown, Lord Howe Island is built of basalt almost typical of Chayes' petrographically " oceanic types ", it has as stated a tendency towards his petrographically " circumoceanic " class. It may be noted that the alkaline eastern Otago suite of South Island, New Zealand, which the Lord Howe basalts closely match, provides one of the main exceptions to Chayes' conception, since it is geographically circumoceanic, but petrographically oceanic. The close match between the Lord Howe Island basalts and those from south eastern Australia calls for comment, because the latter are clearly circumoceanic. However Macdonald (1949), confirming the findings of Edwards (1935), has pointed out that the olivine basalt-trachyte associations, typical of the Pacific province (and other ocean basins) are not wholly restricted to these oceanic areas, but are found, additionally, in some continental settings, but only in areas that have experienced no major orogeny for very long periods previous to the eruptions, whereas the calc-alkaline magmas typically accompany and follow orogeny. The south eastern Australian region has not been subject to any orogenic epoch since the late Devonian and is a region of Mesozoic and Tertiary stability.

The remaining matches that have been noted (Table X) for the Lord Howe Island rocks are with truly oceanic basalts (Nockold's " alkali andesites " are mainly from Hawaii) and therefore call for no special comment.

Whereas Lord Howe Island lies well to the west of the crest of the Lord Howe Rise, Norfolk Island lies on the crest of the Norfolk Island Ridge. Analyses of the Norfolk Island volcanics would therefore be particularly desirable, in order to compare the degree of silica saturation of the parental rock and its most differentiated member with the values obtained for Lord Howe Island. McBirney and Gass (1967) have shown a clearly increased silica saturation from basaltic and differentiated rocks on and near the crests of the East Pacific Rise and the Mid-Atlantic Ridge. An extension of their methods to the south west Pacific should help to show whether their findings are of more general application.

VI. NOTES ON THE OLDER SERIES

Inclined altered series The older series of tilted lavas and dykes (Pl. 15,2) are not a pleasing study owing to their alteration, mainly to carbonates and chlorite with less common conversion of the pyroxene to calcite. Olivine, where present, is completely altered to a talc-ore residuum. In those flows in which plagioclase and pyroxene are sufficiently fresh to allow optical determination the results confirm that their composition is similar to that of the younger Gower-Lidgbird lavas.

Thus the highest flow exposed at Boat Harbour (BM.1966, P5, 42) has pyroxene with a mean 2V of 52½° as well as two generations of plagioclase. The groundmass crystals are mostly zoned with cores averaging An 50 and exteriors as sodic as An 35. The phenocrysts have a mean composition of An 72 and there may be some xenocrysts since one crystal was found to be as calcic as An 82. The groundmasses of two other flows at this locality contained plagioclase of mean composition An 49 and An 50. Only the lowest flow examined (BM.1966, P5, 46) about 200 feet below BM.1966, P5, 42) had small plagioclase grains averaging An 58 (An 53–64). With this one exception, therefore, the composition of the plagioclase accords exactly with the mean composition of the Gower-Lidgbird plagioclase and the optic axial angle of the pyroxene is also in good agreement with that of the phenocrystal pyroxene from the younger lavas.

Therefore in spite of the long time interval which must have elapsed between the outpouring of these older lavas (expressed by their tilting and partial denudation), and the mid-Pliocene Gower-Lidgbird series there is no reason to think that they differed in composition in any material respect from the younger, flat lying alkali olivine basalts which partly overly them. However the large proportion of coarse agglomerate in the inclined series bears witness to the fact that explosive volcanic activity was much more prevalent at this earlier epoch than it was in the later mid-Pliocene phase of vulcanism.

Horizontal altered series. The older horizontal series also shows considerable alteration and the flows tend to have rubbly, lateritized upper portions—evidence of long periods of subaerial erosion. The few fairly fresh specimens collected were mainly from near sea level except at Malabar, where the summit (about 700 feet above sea level) is formed of a vesicular, porphyritic plagioclase-pyroxene-basalt, devoid of olivine, but with much granular ore altered to haematite (BM.1966, P5, 50). The phenocrysts occur in glomero-groups. In places there is a suggestion of flow structure. At Ned's beach a similar porphyritic basalt occurs, but here olivine is present, both as phenocrysts showing incipient iddingsitization, and in the groundmass where alteration to iddingsite is advanced. All specimens from this series contain a proportion of irresolvables, often green in colour. The fabric is usually intergranular.

Determinations of the optic axial angle of the pyroxenes from the top of the series

(Malabar) gave a mean value of 53¼° while a value of 53° was obtained from the base of the series, at the Old Gulch. The pyroxene is therefore presumed to be of uniform composition throughout the 700 feet of lavas here exposed. Moreover, as in the inclined series, this value of 2V exactly matches the mean value of the pyroxene phenocrysts from the younger Gower-Lidgbird series. Although no determinations have been made on the plagioclase, there seems no reason to doubt that the fresher basalts of the older horizontal series are similar to the Gower-Lidgbird basalts although they probably contain less olivine.

VII. BALL'S PYRAMID

The dramatic spire of Ball's Pyramid (Pl. 14, 1) over 1800 ft in height rises approximately 12 miles south of Mt Gower ; the sea between Mt Gower and Ball's Pyramid has a maximum depth of about 800 ft. The pyramid was visited on August 13th 1965, but a relatively heavy swell and an extremely steep face allowed a brief landing only by one member of the party at considerable risk.

The SW flank of the pyramid is sheer for 1800 ft. This stupendous cliff is considerably obscured by guano, but from a range of 20 to 30 yards the presence of 7 dykes could be established. These are all relatively thin, almost vertical and their strike is approximately perpendicular to this South West face, i.e. the strike is roughly NE–SW. The dykes are about 20 yds apart. This spacing is the same as that on the north cliff of Lord Howe Island, although the strike differs in the two localities. The lavas which they intersect are virtually horizontal, and appear to be considerably altered. These facts suggest that Ball's Pyramid does not belong to the Gower-Lidgbird series of younger volcanics, but to an older eruptive period. It is probable that the pyramid formed part of the older horizontal series, which builds the northern part of Lord Howe Island. The dyke rock collected from the south east corner of the pyramid (BM.1966, P5, 105) shows, in thin section (Pl. 10, 2) glomero-groups of labradorite (mean composition An 62), but no xenocrysts of a more calcic composition. The groundmass is composed of fresh plagioclase laths (mean composition An 54), sparse pyroxene grains and a large proportion (probably 50%) of a brownish semi-opaque product with much ore, and a pale yellow substance having an interior zone with aggregate polarization. Flow structure is weakly developed.

VIII. AGE OF THE ISLAND

It has been previously mentioned that the Gower-Lidgbird lavas form the youngest volcanic group on the island, since these flows are not cut by the dyke swarms which intersect the older lavas. The horizontal altered series is relatively older than the Gower-Lidgbird sequence, and although the age gap cannot be established it may not be as great as considered by David (1889). The Boat Harbour dipping lavas are of considerably greater antiquity than either of the horizontal series. Two agglomerate masses that were examined at the south end of Blinkenthorpe beach (Pl. 14, 2) and NW of Mt Lidgbird have concealed field relationships and it is impossible to establish their positions in the relative age groups. Since they are intersected by altered sheets and dykes they probably belong to an initial phase in the volcanic history of the island. Fortunately the Gower-Lidgbird lavas of Lord Howe Island are sufficiently fresh for K/Ar dating. In view of the fact that some contain a little devitrified glass it was felt that the most reliable ages would be those determined from the plagioclase, and not from whole-rock samples. The fresh plagioclase from the analysed oceanite (BM.1966, P5, 8) 2200 ft above sea level was separated ; its K_2O content determined by flame photometry and its K/Ar ratio determined by J. A. Miller and F. J. Fitch. The results of two runs are given in Table XI.

TABLE XI

DETERMINATION OF AGE OF OCEANITE FROM GOWER-LIDGBIRD SERIES

K_2O (wt. per cent)	Air correction (per cent)	$\frac{\text{Vol. radiogenic } ^{40}\text{Ar (mm}^3\text{)}}{\text{Wt. of sample (gms)}}$	Age and Error m.y.
0·96	82·6	$2{\cdot}48 \times 10^{-4}$	7·75 ± 0·18
—	85·2	$2{\cdot}43 \times 10^{-4}$	7·60 ± 0·17

This younger volcanic series in the island is therefore of mid-Pliocene age. An attempt was made to date the horizontal altered series from separated plagioclase. This age was of the same order as that for the Gower-Lidgbird sequence. The results must be regarded as very approximate (error of ±2·5 m.y.) since the plagioclase is slightly altered and the amount that could be separated (0·03 gm) was extremely small. It is unfortunate that the inclined altered series contains no feldspar fresh enough for an age determination. The youngest alkali olivine basalts of Lord Howe Island are, therefore, intermediate in age between the nearest lavas from NE New South Wales (McDougall and Wilkinson, 1967), where the youngest volcanics have ages of the order of 13·5 to 15 m.y. and the extensive Victorian " new " volcanic series, which mainly consists of alkali olivine basalt with ages ranging from 4·5 to 0.56 m.y. (McDougall *et al.*, 1966). In New Zealand the North Island volcanics are mainly Recent, but the Lyttleton group of Banks Peninsula in South Island has been tentatively ascribed to the Pliocene (Curtis, 1965), although no radiogenic dating appears to have been made. This suite consists mainly of andesites and basalts ; olivine basalt flows are extremely rare. In the Dunedin field (Benson, 1946) the only two lavas that have been dated by radiogenic means (Curtis, 1965) are a trachyte from the initial eruptive phase, with an age of 15 m.y. and a phonolite from the third (and final) phase, which has an age of 11·1 m.y.

In the Hawaiian chain (McDougall, 1964) the Mauna Kuwale trachyte, which outcrops on Oahu, has a mid-Pliocene age (8·36 m.y.) but, with this one exception, the lavas from the rest of this chain are younger ; the oldest occurs on Kauai and gives a mean value of 5·62 m.y.

The inclined, altered series of lavas and agglomerates is evidence of an additional much earlier phase of volcanic activity on the present site of Lord Howe Island. As mentioned earlier the Gower-Lidgbird series (and the horizontal altered series forming the northern part of the island) are virtually horizontal over the whole area of their outcrops (Pl. 13). This horizontality over such a large surface implies

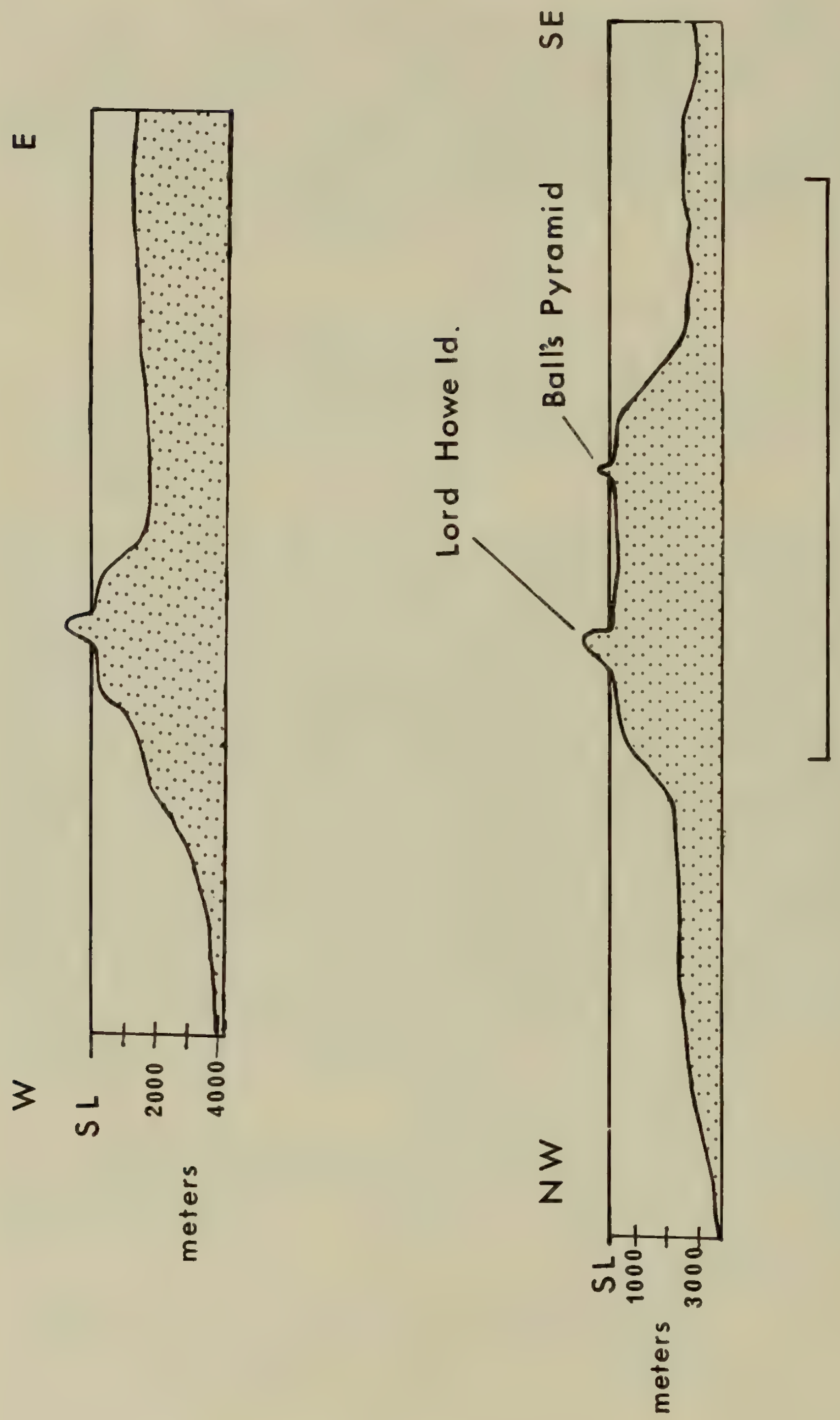


Fig. 21. Sections across Lord Howe Island and the adjacent sea bed (Vertical scale 4× horizontal scale).

the existence of an exceedingly liquid magma, probably of fissure eruption type, flowing over a level surface. It seems reasonable to suppose that the younger dyke swarm acted as feeders for the flows in view of the close similarities already noted in the minerals of both. In the south west (but not in the east) the inclined lavas and agglomerates were probably reduced to sea level before the younger flows covered them horizontally. If we accept Gass' (1967) assumption that ocean islands once they become inactive require from 20 to 25 million years for their reduction to atolls, the older lavas and agglomerates must have an age not less than about 30 million years, since it has been shown that their partial covering by the younger Gower-Lidgbird series took place at least 7 million years ago. It would therefore seem probable that volcanic activity on the present site of Lord Howe Island had started in the mid-Tertiary, and that the main product of this earlier phase was also alkali olivine basalt essentially similar to the Pliocene lavas. The younger volcanics of Lord Howe Island, formed about 8 million years ago, have on Gass' assumptions lost at least half their original volume, since the rate of decay is likely to be exponential. Mounts Gower and Lidgbird were probably more than twice their present heights, thus matching Recent cones such as Tahiti and Tristan da Cunha (about 7000 ft); consequently as much as 4000 ft of upper lavas may have been removed. The evidence points to a trachytic late differentiate which has probably been eroded from the summits of the two mountains. The younger volcanics that are preserved, after this extensive erosion, show only relatively slight differentiation, the latest product being a trachyandesite, with the possible exception of a thin, altered trachyte near the summit of Mt Gower. The older lavas have, naturally, suffered far greater erosion than the Gower-Lidgbird sequence. The latest bathymetrical chart of the Lord Howe Island area (Text-fig. 2), and the two sections drawn across this chart (Text-fig. 21), show that the base of the original volcano measured approximately 30 miles from north to south by 10 miles from east to west. The present island (about 7 sq miles) consequently occupies only about one fortieth of its original area and a much smaller fraction of its original volume. In this connection it may be compared with Inaccessible Island (in the Gough Island group), which, with a radiometrically determined age of 3 m.y. is considered by Gass (1967) to have lost 90 to 95% of its original volume and to have had a postulated original height of 7500 ft reduced to 1800 ft.

IX. SUMMARY AND CONCLUSIONS

The results of this investigation suggest the following conclusions.

1. Lord Howe Island is composed of the following units :

(*a*) Fresh alkali-basalts, mid-Pliocene according to radiometric age determinations, build Mounts Gower and Lidgbird at the southern end of the island. The flows are horizontal and the series is nearly 3000 ft thick. Its original thickness was probably twice as great.

(*b*) An older horizontal, partly altered basaltic series (possibly of Pliocene age) forms the northern part of the island and probably also outcrops at Ball's Pyramid 12 miles south of Mt Gower.

(*c*) A series of inclined altered basaltic flows, outcrop in the SE of the island, where at least a thousand feet are exposed. Near the base of this series coarse agglomerates are abundantly developed.

(*d*) Dykes traverse each of the above groups with the exception of the youngest series (series *a*). Only the younger dykes, i.e. those that cut series *b* consist of fresh basaltic types. The remaining dyke-rocks show alteration in varying degrees.

Detailed examination has been confined to the fresh rocks, namely the Gower-Lidgbird lavas and the younger dyke swarm.

2. Considerable mineralogical and textural variations occur in the Gower-Lidgbird series, which includes both non-porphyritic lavas, and other lavas in which phenocrysts account for about one-quarter of the whole. Oceanites and oceanite-ankaramites form at least five different horizons and are believed, from chemical considerations, to have been formed by the accumulation of olivine and pyroxene in basaltic magma, without assimilation of lime or other material.

3. Minor differentiation towards a trachytic residuum occurs towards the top of the Gower-Lidgbird series. At the top of this series the plagioclase is albitized.

4. The younger dykes are fresh, usually narrow, steeply dipping, non-composite and show a tendency to be radial about Mt Lidgbird. In certain places the swarm is so dense that only remnants of the older lavas can be discerned between them.

5. In the majority of these dykes olivine is rare or absent ; about 85% of the dykes are porphyritic, having plagioclase as the commonest phenocryst. Some dykes contain up to 15% (modal) of primary, iron-rich magnesian carbonate. Many dykes have spherical vesicles infilled by deuteric minerals with carbonate always at the centre. In the rare olivine-bearing dykes olivine phenocrysts form up to 30% of the rock. In all the dykes olivine is absent or sparse in the groundmass.

6. The olivine bearing dykes preceded the non-olivine types in order of intrusion.

7. The average chemical composition of the fresh basalts (from both lavas and dykes) is similar to the average alkali andesites given by Nockolds (1954). Other basaltic types with comparable compositions occur in East Otago (New Zealand), central Victoria (Australia), Tutuila (Samoa) and the circum-Japan sea province.

8. Vulcanism is considered to have been active for at least 25 million years, and to have ended in the mid-Pliocene. The Lord Howe Rise is of considerable antiquity (probably Paleozoic). A low angle unconformity reported from the north east flank of the rise implies former elevation of the crest above sea level. This could be the source for the sediments that accumulated in the New Zealand Permian and early Mesozoic geosyncline.

9. Throughout the period of vulcanicity there is no evidence of change in the overall composition of the lavas ; the older lavas (in spite of alteration) appear to have belonged to the alkali-basalt group.

10. In the distribution of selected oxides used by Chayes (1964) to distinguish petrologically oceanic from petrologically circum-oceanic lavas, Lord Howe Island, though conforming closely to the oceanic group shows a slight displacement *in each oxide* towards the peak value for the circum-oceanic basalts. This may be connected with the position of Lord Howe Island in a Mediterranean type sea floor rather than in a true oceanic environment.

11. Lord Howe Island exemplifies the concept that Cainozoic volcanic islands are sparse off continental ocean borders not marked by a deep-sea trench, and that those which do occur are likely to be petrographically oceanic.

12. The relation between the degree of silica undersaturation of the Lord Howe Island average basalt and its distance from the crest of the submarine ridge is similar to the relation between these two variables in the islands close to the Mid-Atlantic Ridge and the East Pacific Rise.

13. The composition of the plagioclase phenocrysts from the Gower-Lidgbird lavas varies from about An 65 at the base of the series to about An 55 at the top. This variation is not regularly progressive but rhythmical. Xenocrysts with compositions from An 70 to An 80 only occur at the base of the series. The groundmass plagioclase has an average composition of An 50 almost throughout the series, becoming slightly more sodic near the top.

14. The larger plagioclase crystals of the dykes occur as : (*a*) phenocrysts, (*b*) xenocrysts, (*c*) spongy or checkerboard crystals and (*d*) crystals with oscillatory zoning. Variations in the values of 2V and of $\perp 010\wedge\alpha$ and $\perp 010\wedge\beta$ exceed experimental error, and are considered to be due to variations in the degree of ordering of the lattice. This implies differing thermal histories and suggests different depths of derivation for the phenocrysts.

15. The fresh pyroxenes of both the Gower-Lidgbird volcanics and of the younger dyke rocks show no optical variations exceeding the experimental error. The phenocrysts have an average composition of $Ca_{42}Mg_{49}Fe^{2}_{9}$ whilst the groundmass pyroxenes have a composition of $Ca_{44}Mg_{43}Fe^{2}_{13}$. In a zoned phenocryst electron-probe analysis gave a Mg : Fe ratio of 1·46 for the centre and 1·21 for the margins. Two chemical analyses of phenocrysts and groundmass pyroxenes are given. The compositions, trend (parallel to the Di-Hd join), and the relation between pyroxene and the magma from which it separates (pyroxene is richer in lime) are all typical features of pyroxenes from alkali basalts.

16. In the Gower-Lidgbird volcanics the olivine shows no significant variation in the flows of the upper 1300 ft where it averages 26% (mol) Fe_2SiO_4. In the lower 1500 ft (in which the flows are richer in olivine) it changes in composition from 18 to 28% Fe_2SiO_4 with a mean value of 23% Fe_2SiO_4. Groundmass olivine has a composition of 36% Fe_2SiO_4. Olivine phenocrysts from the dyke rocks, except those at North beach, have a mean composition of 22½% Fe_2SiO_4. The North beach olivines are slightly, but significantly richer in magnesium with a mean composition of 18% Fe_2SiO_4.

17. Iron ores fall into two groups ; the first has a composition close to that of ilmenite, whilst the second approximates to a Ti-poor Fe-rich ulvöspinel. The ilmenites of the dyke rocks have slightly more Fe and less Ti than do those of the lavas. The composition of the ulvöspinel shows no difference as between dykes and flows. In the Gower-Lidgbird lava sequence there is (apart from a few exceptions) a definite trend from ilmenite bearing flows in the lower layers to ulvöspinel bearing lavas near the top.

18. 2V is of only secondary value as a guide to the composition of calcic plagioclases.

19. The values of the cell sides and of the angle β are a more reliable guide to the composition of monoclinic pyroxenes than are their optical properties (refractive index and 2V).

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APPENDIX 1

Petrography of Gower-Lidgbird lavas.

Registration No. BM.1966, P5, (A = anal. specimen)	Height above sea level	Phenocrysts			Mesostasis and Remarks
		Olivine	Pyroxene	Plagioclase	
1. (A) andesine-basalt	2700 ft	—	—	—	Contains xenoliths of hypersthene, plagioclase (An 53) and diopsidic pyroxene, the whole surrounded by a rim of granular olivine. Flow is well marked and there is a relatively large amount of greenish devitrified glass. Olivine is more abundant than pyroxene. The plagioclase is considerably albitized : non-albitized portions have a composition of An 50.
2. (A) alkali-olivine-basalt	2600 ft	15% mean diameter 0·4 mm. fresh ; crystals partly resorbed.	< 1%	—	Contains some isotropic glass and spherular vesicles. Plagioclase has an approximate composition of An 50. No flow structure. The ore is ulvöspinel ; there is no ilmenite. Chemically similar to " basic labradorite basalts ", Camperdown type, Victoria, Australia, described by Edwards (1938).
3. alkali-olivine-basalt	2500 ft	15% mean diameter 0·6 mm. Narrow iddingsite rims ; crystals partly resorbed.	—	—	Contains some isotropic glass. The groundmass is very dense with much ore. Contains spherular vesicles.
4. trachybasalt	2450 ft	4% mean diameter 1·0 mm. Completely serpentinized.	3% mean diameter 1·0 mm. Idiomorphic.	14% mean length of idiomorphic prisms = 1·5 mm.	The plagioclase phenocrysts show alignment, but the groundmass feldspar (partly albitized) shows only a feeble flow structure. Contains some isotropic glass ; spherular vesicles are filled by a chlorite. Ore is almost 100% ulvöspinel.
5. trachybasalt	2350 ft	< 1% Iddingsitized.	< 1%	23% mean length of idiomorphic prisms 2·5 mm.	Contains some isotropic glass. There is no flow structure. Olivine is fairly plentiful. The ore consists of about 80% ilmenite and 20% ulvöspinel. The plagioclase phenocrysts often show oscillatory zoning and strong dispersion.
6. trachybasalt	2300 ft	—	—	—	There is a very well developed flow, giving a trachytic texture. There is much devitrified, pale yellow-green, intersertal glass.

APPENDIX I (contd.)

Registration No. BM.1966, P5, (A = anal. specimen)	Height above sea level	Phenocrysts			Mesostasis and Remarks
		Olivine	Pyroxene	Plagioclase	
7. olivine-basalt	2250 ft	2½% variable size up to 2 mms. Iddingsitized.	1%	14% narrow prisms averaging 1·5 mm. in length.	Holocrystalline. Sub-ophitic fabric. Ore is mainly ilmenite. Modal composition : plagioclase 45%, pyroxene 32½%, olivine 5½%, ore 14½%, irresolvables 2½%. The distinction between plagioclase of two generations is often difficult.
8. (A) oceanite	2200 ft	32% mean diameter 1 mm. Iddingsite rims.	5% mean diameter 1·2 mm.	—	Cumulate type. The intercumulate material is holocrystalline with sub-ophitic fabric and a little iddingsitized olivine. The composition of the plagioclase varies progressively from An 44 in the smallest grains to An 67 in the largest. It is not possible to recognize two generations. Ore is mainly ilmenite.
9. trachybasalt	2150 ft	3% mean diameter 0·7 mm. Iddingsitized.	½%	4% mean length of idiomorphic prisms 1·1 mm.	Has well marked flow structure. Markedly vesicular type (vesicles empty). Probably contains no glass. Ore is abundant and is probably ulvöspinel, without ilmenite.
10. olivine-basalt	2100 ft	14½% mean diameter 1·0 mm. Narrow iddingsite rims.	2% mean diameter 1·0 mm.	—	Has quite well developed flow. The groundmass is very fine with an intergranular fabric and some isotropic glass. Iddingsitized olivine is quite plentiful.
11. trachybasalt	2050 ft	5% mean diameter 1·0 mm. Extensively iddingsitized.	3½% mean diameter 1 mm.	13½% mean length of idiomorphic prisms = 2 mms.	Flow structure is quite marked. Glass is probably absent, but there is some material of low relief. Iddingsitized olivine is quite plentiful.
12. olivine-trachybasalt	2000 ft	14½% mean diameter 1·0 mm. Largest crystals 2½ mms. Narrow iddingsitized rims.	< 1%	—	Flow structure is only weakly developed and sporadic. The fabric is intergranular. Glass is probably absent. Olivine is sparse. The groundmass is somewhat heterogenous with mafic zones. The ore is about 90% ulvöspinel and 10% ilmenite.
13. oceanite-ankaramite	1950 ft	35% mean diameter 1·0 mm. partly iddingsitized.	10% 1 to 3 mms. in diameter	—	Cumulate type. Very similar to BM.1966, P5, 8. The intercumulate material shows sub-ophitic fabric and contains sparse, iddingsitized olivine. There is no glass.

APPENDIX 1 (contd.)

Registration No. BM.1966, P5, (A = anal. specimen)	Height above sea level	Phenocrysts Olivine	Pyroxene	Plagioclase	Mesostasis and Remarks
14. (A) trachybasalt	1920 ft	—	—	—	Very well marked flow structure, giving a trachytic texture. Plagioclase is fine-grained, strained and probably partly albitized. There is no glass. Olivine is abundant in the groundmass and is greatly in excess of pyroxene. The ore is entirely ulvöspinel and there is no ilmenite : veinlets contain aegirine-augite.
15. alkali basalt	1900 ft	4% mean diameter ½ mm. largest 1½ mm. Partly iddingsitized.	4% 1 to 3 mms. in diameter. Zoned.	4% mean length 2 mms.	Flow structure well marked. There is a very little pale fawn-coloured isotropic glass.
16. alkali olivine-basalt	1800 ft	23% mean diameter 1½ mm.	—	—	There is no flow structure. The groundmass is relatively coarse-grained and contains a little straw-coloured devitrified glass. Olivine is present in the groundmass but sparse. The ore is entirely ilmenite and there is no ulvospinel.
17. oceanite-ankaramite	1730 ft	36% mean diameter 1.0 mm. partly iddingsitized.	10% mean diameter 1½ mm.	—	Cumulate type. Very similar to BM.1966, P5, 8 and 13. The intercumulate material shows ophitic fabric. Olivine in sparse and iddingsitized.
18. plagioclase-pyroxene-basalt	1700 ft	6% mean diameter 1·0 mm. largest 2½ mms. partly iddingsitized.	4% mean diameter 1½ mm.	12½% mean length 2½ mms.	Flow is weakly developed. There is no glass. Olivine is present in the ground mass, but subordinate to pyroxene.
19. alkali olivine-basalt	1500 ft	6½%	—	—	Flow structure is weakly developed. There is no glass. Olivine, partly iddingsitized, is approximately equal in amount to pyroxene. The groundmass contains some primary carbonates and carbonate also forms the rim of some spherular vesicles. Ore is abundant, fine-grained and consists entirely of ulvospinel without ilmenite.

APPENDIX 1 (contd.)

Registration No. BM.1966, P5, (A = anal. specimen)	Height above sea level	Phenocrysts			Mesostasis and Remarks
		Olivine	Pyroxene	Plagioclase	
20. alkali olivine-basalt	1490 ft	< 1% partly iddingsitized.	—	—	Flow structure is well marked. There is no glass. Olivine, iddingsitized, is probably in excess over pyroxene. Rather irregular vesicles are filled by chabazite. The ore consists of approximately 80% ulvöspinel and 20% ilmenite.
21. alkali olivine-basalt	1475 ft	< 1% slightly iddingsitized.	—	—	Flow structure is well marked. There is no glass. Olivine probably exceeds pyroxene in amount. Vesicles are filled by carbonate associated with a zeolite (chabazite). The ore consists, approximately, of 75% ulvöspinel and 25% ilmenite.
22. (A) alkali olivine-basalt or alkali-andesite	1455 ft	1·0% completely serpentinized.	—	—	Flow structure is well marked. There is a very small quantity of fawn-coloured glass, slightly devitrified. The plagioclase grains are too small for optical determination. Olivine is about equal to pyroxene in amount. The ore consists approximately of 50% ulvöspinel and 50% ilmenite. Closely matches, chemically, the " average alkali-andesites ", listed by Nockolds (1954).
23. alkali olivine-basalt	1360 ft	2½% mean diameter 0.3 mm. Iddingsitized.	—	½% ½ to 2 mms. in length.	Flow structure is very well developed. The groundmass is similar to that of the preceding flow.
24. alkali-basalt	1350 ft	2¼% mean diameter 1·0 mm.	¾%	½% ½ to 2 mms. in length.	Flow structure is very well developed. There is about 5% of emerald-green, devitrified glass. Olivine is probably absent. A radiating zeolite (chabazite) occurs. There are some irresolvable products.
26. (A) alkali olivine-basalt	1210 ft	2¾% ½ to 2 mms. Fresh but partly resorbed.	—	—	Flow structure is well marked. At least 5% of partly devitrified, emerald-coloured glass occurs. Partly serpentinized olivine is quite plentiful, but less abundant than pyroxene. Occasional vesicles contain radiating chabazite. The groundmass resembles those of BM.1966, P5; 22 and 23. The plagioclase has a mean composition of An 48. A close match chemically,

APPENDIX 1 (contd.)

Registration No. BM.1966, P5, (A = anal. specimen)	Height above sea level	Phenocrysts			Mesostasis and Remarks
		Olivine	Pyroxene	Plagioclase	
					for the alkali olivine-basalt average of the Hawaiian lavas, as given by Macdonald (1949) and the mean of the Trentham and Camperdown olivine-labradorite-basalts described by Edwards (1938).
27. (A) alkali olivine-basalt	1120 ft	2¾% mean diameter 0·7 mm. Fresh but partly resorbed.	—	—	Flow structure is well marked. 5 to 10% of devitrified, emerald-coloured glass occurs. Partly serpentinized olivine is quite plentiful, but less abundant than pyroxene; plagioclase averages An 49 but a few grains are zoned from An 32 to An 58. Occasional vesicles are filled by a zeolite (chabazite) sometimes radiating. Closely matches, chemically, the olivine-labradorite-basalt (Trentham type) described by Edwards (1938).
28. olivine-labradorite-basalt	1100 ft	18% mean diameter 1¾ mm. Has narrow iddingsite rims.	6½% mean diameter 1·0 mm.	12% mean length 1½ mm. Longest 3 mms.	There is no flow structure. There is a small proportion (1 to 2%) of very pale, lemon-coloured glass, almost isotropic. Olivine, partly iddingsitized, is quite plentiful, but less than pyroxene in amount. The ore is about 50% ulvöspinel and 50% ilmenite.
29. labradorite-basalt	1080 ft	3½% mean diameter 1·0 mm. Slight alteration to iddingsite and partly resorbed.	6½% mean diameter 1·2 mm.	8½% mean length 1·5 mm.	Flow structure is fairly well developed and the plagioclase phenocrysts also show alignment. There is a very small amount (<1%) of colourless isotropic glass. Olivine, iddingsitized, is quite plentiful but less than pyroxene in amount. The groundmass contains biotite in small quantity. The ore is about one-third ulvöspinel and two-thirds ilmenite.
30. labradorite-olivine-basalt	1060 ft	8% mean diameter 1·5 mm. Partly iddingsitized	5½% mean diameter 1·0 mm.	17% length varies from 1 to 6 mms. mean length 1·5 mm.	There is no flow structure and, probably, no glass. The groundmass is similar to those of BM. 1966, P5; 28 and 29. The phenocrysts tend to form glomero-porphyritic groups. Olivine is quite plentiful. The ore is almost 100% ilmenite.
31. augite-olivine-basalt	1000 ft	8% mean diameter 0·8 mm. Iddingsitized, sometimes completely.	10% mean diameter 1·2 mm. Largest 3 mms.	4% mean length 1·2 mm.	Flow structure is fairly well developed. There is a small proportion of pale yellow, devitrified glass. Olivine is quite plentiful. Similar to BM.1966, P5; 28 to 30.

APPENDIX 1 (contd.)

Registration No. BM.1966, P5, (A = anal. specimen)	Height above sea level	Phenocrysts			Mesostasis and Remarks
		Olivine	Pyroxene	Plagioclase	
32. alkali olivine-basalt	950 ft	9% mean diameter 0·8 mm. Partly iddingsitized.	2% 0·6 to 2·6 mms.	—	There is no flow structure and probably no glass. Olivine is present, but is considerably less in amount than pyroxene. The groundmass is relatively coarse-grained and its contrast with the phenocrysts is not very pronounced.
33. oceanite-ankaramite	720 ft	44% mean diameter 1·5 mm. Rims of iddingsite.	14% mean diameter 4 mms.	—	Cumulate type. The intercumulate material shows no flow ; it contains a little, partly iddingsitized olivine. The fabric tends to be intergranular rather than ophitic. In other respects this cumulate resembles BM.1966, P5 ; 8, 13 and 17.
34. alkali basalt	650 ft	7½% mean diameter 0·7 mm. Rims of iddingsite.	1%	—	There is no flow structure and no glass. The fabric is a 'mixture' of intergranular and sub-ophitic. Iddingsitized olivine is sparsely present. The ore is 100% ilmenite ; there is no ulvöspinel. The groundmass is relatively coarse-grained and there is little contrast with the phenocrysts.
35. alkali basalt	570 ft	5% mean diameter 1·0 mm. Rather extensively iddingsitized	10% mean diameter 0·5 mm. but much larger phenocrysts occur, up to 5 mms. in diameter.	1%	There is no flow structure and no glass. Partly iddingsitized olivine is quite plentiful but less abundant than the pyroxene. The ore (mainly ilmenite) is " ragged " and ophitically encloses plagioclase and sometimes pyroxene.
36. oceanite	500 ft	50% mean diameter 2 mms. Maximum about 5 mms. Narrow rims of iddingsite.	2% mean diameter 1 mm.	—	Cumulate type. The intercumulate material has no flow and no glass, and its fabric is intergranular rather than subophitic. It contains a little partly iddingsitized olivine and a radiating zeolite (chabazite). The ore consists of about 60% ulvöspinel and 40% ilmenite.

APPENDIX I (contd.)

Registration No. BM.1966, P5, (A = anal. specimen)	Height above sea level	Phenocrysts			Mesostasis and Remarks
		Olivine	Pyroxene	Plagioclase	
39. alkali olivine-basalt	330 ft	8% mean diameter 2 mms. Rims of iddingsite.	5% diameter 0·2 to 0·5 mm.	3% mean length 0·5 mm.	There is no flow structure and no glass. Iddingsitized olivine is quite abundant, about equal in amount to pyroxene. The fabric is intergranular. The fine-grained phenocrysts tend to form glomero-porphyritic groups. Ore is 100% ilmenite ; there is no ulvöspinel.
38. alkali basalt	315 ft	0·2% partly iddingsitized.	—	2% up to 1·5 mm. in length.	There is a fairly well developed flow structure. There is no glass. Rather sparse olivine forms relatively large grains. The fabric is intergranular. There is a high concentration of granular ore, both ulvöspinel and ilmenite being present ; but the proportions are uncertain.
37. (A) andesine-basalt	300 ft	2% up to 2 mms. in diameter ; fresh.	—	1% up to 1 mm. in length.	There is a poorly developed flow structure. There is a small proportion of colourless, devitrified glass. The plagioclase phenocrysts have a mean composition of An 61 whilst the goundmass plagioclase averages An 48. Partly iddingsitized olivine forms elongated crystals and is subordinate to pyroxene. The fabric is intergranular. There are occasional vesicles.
40. (A) andesine-basalt	270 ft	2½% mean diameter 0·7 mm. Serpentinized, sometimes completely.	2½% diameter 0·2 to 0·5 mm.	2½% length 1 to 2 mms.	There is no flow structure. Some orange-yellow, partly devitrified glass occurs, and there is also a greenish irresolvable product. The plagioclase phenocrysts have a mean composition of An 59. The groundmass grains average An 50. Olivine is probably absent or altered. The groundmass has a variable grainsize and the distinction between it and the phenocrysts is not great.

APPENDIX 2

Petrography of analysed dyke rocks.

Registration No.	Type	Locality	Description
BM.1966, P5, 64	alkali basalt	North beach	Plagioclase (relatively large grains) show partial alignment ; also occurs in glomero-groups. Somewhat smaller pyroxenes (larger ones show crystal outlines) are set in a fine-grained assemblage of plagioclase, pyroxene, equidimensional iron ore, a little carbonate, very sparse iddingsitized olivine and a small amount of olive coloured glass. Both plagioclase and pyroxene show evidence of strain and probably do not form two generations. Fabric tends to be intergranular. There are some small, empty vesicles.
BM.1966, P5, 80	alkali basalt	Ned's beach	A fine- and even-grained basalt, with partially aligned plagioclase laths, equidimensional grains of pyroxene (showing strain polarisation), and some intergranular greenish product showing aggregate polarisation. Devitrified glass is fairly abundant. Abundant ore consists entirely of ilmenite in " gridiron " form.
BM.1966, P5, 83	alkali basalt with primary carbonate	Blinkenthorpe beach	Microphenocrysts or xenocrysts of plagioclase (An 78–84) usually in glomero-groups, and often associated with pyroxene (of later consolidation) are set in an even-grained base of these minerals and skeletal ore. Olivine is absent. Primary iron rich carbonate is abundant (15% in the mode). There is a small proportion of irresolvable, interstitial residuum. There is no fluxion structure.
BM.1966, P5, 102	alkali olivine-basalt	Admiralty Islets	Abundant, idiomorphic and subidiomorphic olivine phenocrysts showing partial corrosion and serpentinization along cracks ; less abundant, idiomorphic pale brownish-grey pyroxenes and sparse, small plagioclase phenocrysts (An 63) and xenocrysts (An 72–77) lie in a plagioclase-pyroxene-ore groundmass, having a marked fluxion fabric. Intersertal pale green and colourless, devitrified glass is fairly abundant. Ore occurs mainly as elongated shreds.
BM.1966, P5, 89	alkali olivine-basalt	Middle beach	An even-grained basalt with only sparse, small olivine microphenocrysts. The matrix consists of plagioclase laths showing a well marked ophitic relation to a purplish-brown pyroxene. Olivine, fresh or slightly serpentinized is fairly abundant. Ore occurs mainly in elongated forms. There is a little olive-green, devitrified glass and some irresolvables. Sparse vesicles are filled by chabazite. There is no fluxion texture.

PLATE 10

Fig. 1. Vesicle filled by glass, plagioclase laths and semi-opaque products, with carbonate at centre. Plagioclase-basalt ; dyke, North beach ; ordinary light, × 15. BM.1966, P5, 30.

Fig. 2. Plagioclase glomero-group. Plagioclase-basalt ; dyke, Ball's Pyramid ; crossed polars, × 15. BM.1966, P5, 105.

Fig. 3. Plagioclase glomero-group. Basalt ; dyke, North beach ; crossed polars, × 25. BM.1966, P5, 57.

Fig. 4. Spongy plagioclase glomero-group. Plagioclase-basalt ; dyke, North beach ; crossed polars, × 20. BM.1966, P5, 56.

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PLATE 11

Fig. 1. Plagioclase phenocryst, showing discontinuous zoning. Basalt ; dyke, Ned's beach ; crossed polars, × 100. BM.1966, P5, 76.

Fig. 2. Olivine phenocryst, partly serpentinised. Olivine-basalt ; dyke, North beach ; crossed polars, × 10. BM.1966, P5, 71.

Fig. 3. Olivine phenocrysts with iddingsite rims. Alkali olivine-basalt ; flow, Gower-Lidgbird series ; 1800 ft above sea level, ordinary light, × 35. BM.1966, P5, 16.

Fig. 4. Aligned plagioclase phenocrysts. Trachybasalt ; flow, Gower-Lidgbird series ; 2450 ft above sea level ; crossed polars, × 15. BM.1966, P5, 4.

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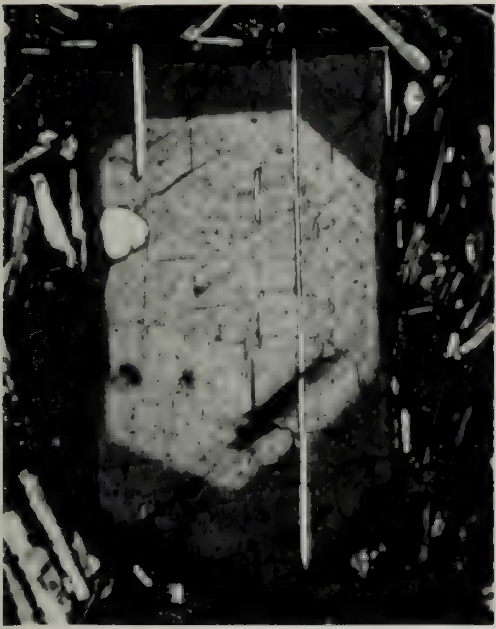

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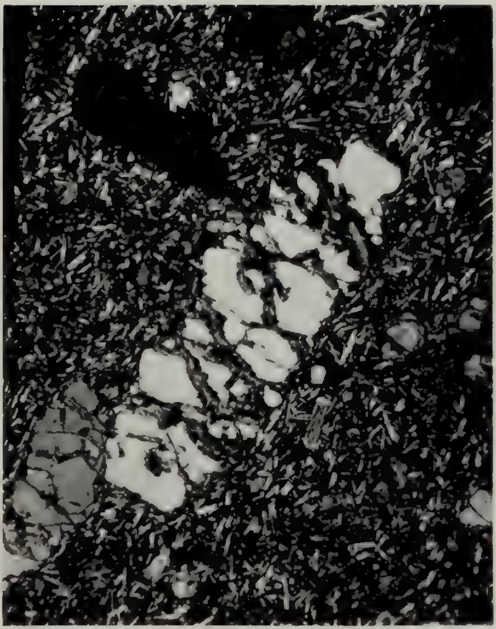

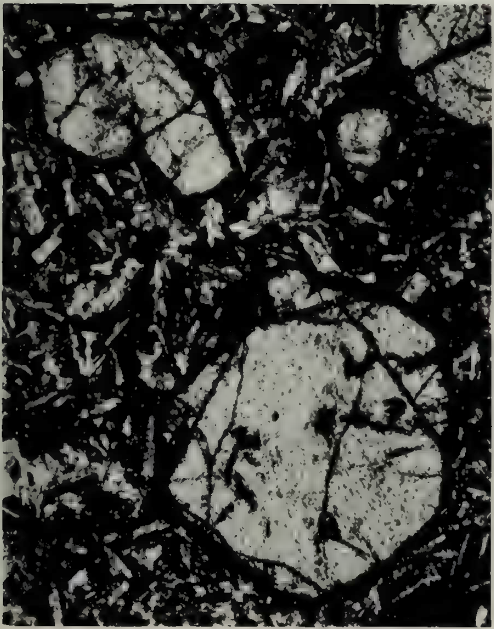

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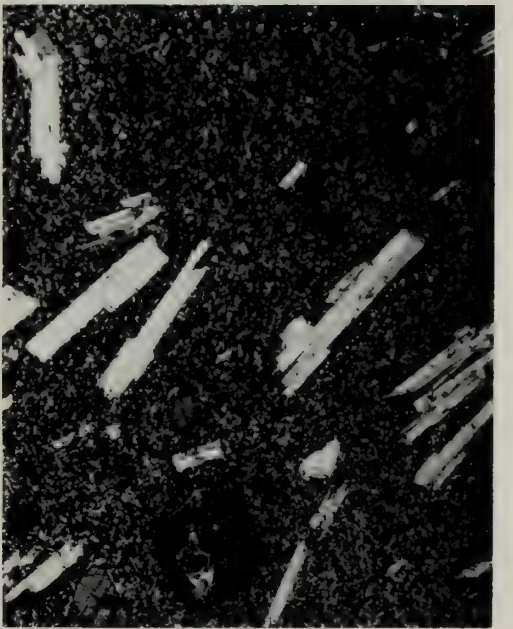

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PLATE 12

FIG. 1. Olivine phenocrysts. Oceanite ; flow, Gower-Lidgbird series ; 500 ft above sea level ; ordinary light, × 12. BM.1966, P5, 36.

FIG. 2. Well developed fluxion texture. Trachy-basalt ; inclined sheet, Gower-Lidgbird series ; 2300 ft above sea level ; crossed polars, × 125. BM.1966, P5, 6.

FIG. 3. Twinned and slightly zoned pyroxene phenocryst. Olivine-pyroxene-basalt; dyke, Admiralty Islets ; crossed polars, × 20. BM.1966, P5, 102.

FIG. 4. Pyroxene glomero-group. Alkali olivine-basalt ; flow, Gower-Lidgbird series ; 330 ft above sea level ; crossed polars, × 60. BM.1966, P5, 39.

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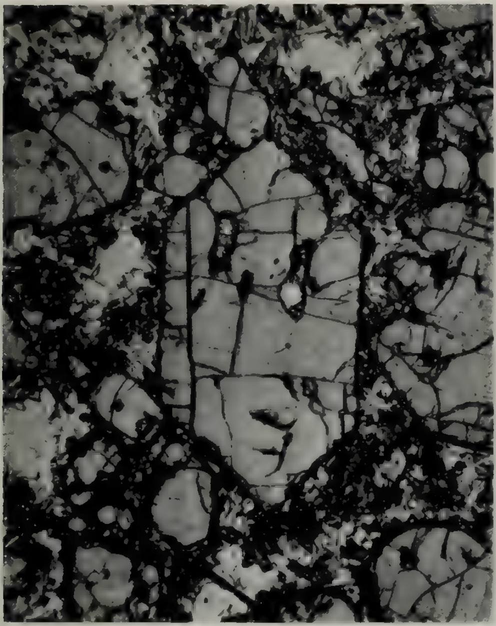

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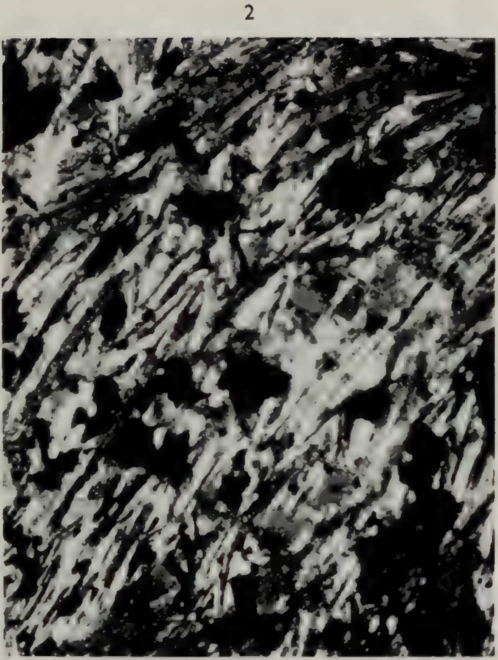

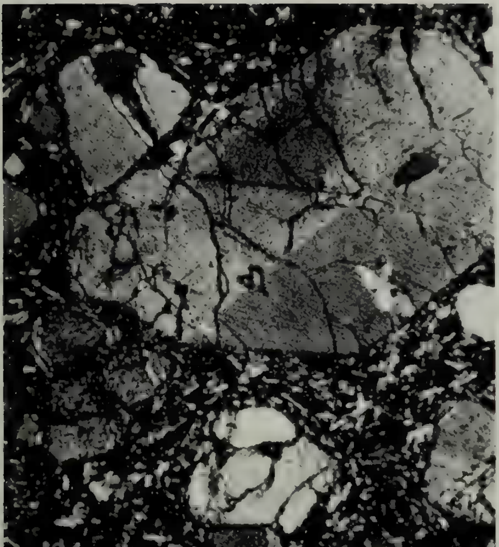

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PLATE 13

FIG. 1. Mt. Gower from the west. Height of cliff section about 2000 ft

FIG. 2. Mt. Lidgbird from the north. Height of cliff section 1100 ft

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PLATE 14

FIG. 1. Ball's Pyramid from the north. Height of pyramid 1860 ft

FIG. 2. Agglomerate, cut by narrow dyke, at south end of Blinkenthorpe beach.

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PLATE 15

Fig. 1. Dense dyke swarm on north side of Rabbit Island. The dykes, most of which are in contact, dip steeply to the west. Height of section about 60 ft.

Fig. 2. Inclined older lavas overlain by darker coloured wedge-shaped agglomerate mass; coast ½ mile north of Boat Harbour.

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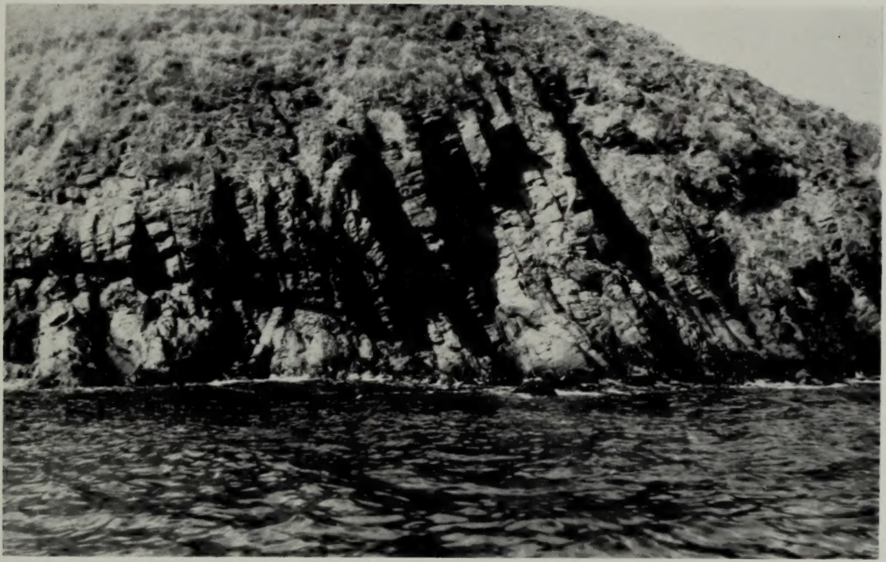

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